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FINE GRINDING OF WOOD CHIPS AND WOOD WASTES WITH THE SZEGO MILL

RENEWABLE ENERGY BRANCH

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PREFACE

In January of 1985, General Comminution Inc. (GCI), in cooperation with the University of Toronto, began a program to test wood grinding with the novel Szego Mill. The main purpose of this report is to describe the results of the wood-grinding test program.

The work was carried out at GCI's laboratory using pilot- and commercial-size mills. The main objective was to establish the performance of the Szego Mill for grinding wood chips and wood wastes to fine sizes.

Within the forest products industries, there is a demand for equipment which is suitable for the fine grinding of wood wastes and wood chips. It is anticipated that the Szego Mill will help meet this demand. An industrial, wood-grinding demonstration unit should be installed and tested in the near future.

ABSTRACT

Grinding wood chips and wood wastes to fine particle sizes is important to the forest products industries. However, reduction of these tough, fibrous materials to small sizes is difficult, and not many types of equipment are available to accomplish the task. The major objective of this study was to test the performance of the Szego Mill, a novel ring-roller mill developed by the University of Toronto and General Comminution Inc., for the above applications.

The technical feasibility of grinding moist ("green") wood chips to a size suitable for chemical conversion, and pelletized wood waste, hog fuel and bark to a size suitable for suspension burning, with the Szego Mill, was demonstrated. Most of the tests were done with the pilot-size (22-cm diameter) mill. Quantitative relationships were determined for the effects of mill rotational speed and product rate on product particle size and mill power consumption for moist aspen chips, 'Energex' pellets and Great Lakes Forest Products hog fuel. The effects of feed moisture content on grinding performance were also investigated.

As an example of the performance of the 22-cm mill, air-dry hog fuel was ground to a size suitable for suspension burning (80 wt% passing 1000 μm) in one pass, at a rate of 365 kg/h, at 1000 rpm, using 8/8 rollers. The specific energy consumption was 46 kWh/tonne oven-dry wood.

Additional tests were made with the commercial-size (46-cm) mill to obtain data for the design of a large, industrial wood-grinding unit. It is anticipated that such a unit will be installed in the near future.

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EXECUTIVE SUMMARY

Grinding wood chips and wood wastes to fine particle sizes is important to the forest products industries. However, reduction of these tough, fibrous materials to small sizes is difficult, and not many types of equipment are available to accomplish the task. The major objective of this study was to test the performance of the Szego Mill, a novel ring-roller mill developed by the University of Toronto and General Comminution Inc. for the above applications.

Most of the work was done with a pilot unit, consisting of a feeding system, a 22-cm-diameter Szego Mill and a product collection system. The effects of various feed, operating and mill design variables on mill capacity, product particle size and mill power consumption were investigated. The major feed variables were the type of material and its moisture content. The major operating variables were the mill rotational speed, and the rate of material and number of passes of material through the mill. Additional tests were made with the commercial-size (46-cm) mill to obtain data for the design of an industrial wood-grinding unit.

The technical feasibility of grinding moist ("green") wood chips to sizes less than 2000 μm, suitable for chemical conversion, and pelletized wood waste, hog fuel and bark to sizes less than 1000 μm, suitable for suspension burning, with the Szego Mill, was demonstrated. Mill product particle size decreases with mill rotational speed and increases with the rate of material through the mill. Power consumption increases with the rotational speed and the rate of material. Quantitative relationships for the dependence of particle size and power consumption on mill speed and rate of material were established for moist aspen chip, 'Energex' pellet and Great Lakes Forest Products hog fuel grinding with the 22-cm mill.

Difficult comminution is indicated by a low degree of size reduction and high power consumption. In order of increasing difficulty of comminution, the materials tested were pelletized wood waste, black spruce bark, hog fuel from northern Ontario, moist spruce chips and moist aspen chips. Wood chips, which are completely fibrous and tough, are much more difficult to grind than wood wastes, which are partly fibrous.

In general, moist materials are more difficult to grind than dry materials. If the moisture content is above a certain level, which depends on the particular material, the degree of size reduction that can be achieved will be limited by the formation of agglomerates from fine particles. In the case of wood wastes, which are ground in order to be burned in suspension, the material should be at least air-dry (approximately 10 wt% total moisture) for efficient grinding and combustion.

Typically, for moist aspen chip grinding with the 22-cm mill, a product with 92 wt% passing 2000 μm (measured by dry sieving) is obtained in two passes, at 1100 rpm, at a rate of 170 kg/h (85 kg/h of oven-dry wood), using 8/16 rollers. The specific energy consumption is approximately 340 kWh/tonne ODW. For air-dry hog fuel grinding, a product with 80 wt% passing 1000 μm is obtained in one pass, at 1000 rpm, at a rate of 365 kg/h, using 8/16 rollers. The specific energy consumption is 46 kWh/tonne ODW.

The energy consumption of the Szego Mill is low compared to that of other types of wood comminution equipment, e.g., a value of 1810 kWh/tonne ODW has been cited for wood chip grinding with a disk refiner (22).

The capacity of the 46-cm mill was three to four times that of the 22-cm mill for Energex grinding. Modifications should be made to the larger mill so that the capacity ratio for hog fuel grinding is similar.

Installation and testing of the Szego Mill in continuous, industrial, wood-grinding applications should now proceed. The 32-cm mill, recently designed and installed at several locations, would be suitable for grinding hog fuel to suspension burner specifications at a rate of about 0.5 tonne/h. A 64-cm wood-grinding unit, capable of grinding hog fuel at a rate of about 2 tonne/h, is planned.

This study is the most comprehensive study yet done of wood grinding with the Szego Mill. The results of tests with the pilot-size mill are very encouraging when compared to the data that are available for other types of comminution equipment. Some additional laboratory work should be done with the 22-cm and 46-cm mills. The areas in which additional tests are required have been identified. However, the emphasis should now shift to the installation of wood-grinding units in industry. The laboratory results have proven that this is feasible.

RÉSUMÉ POUR LA DIRECTION

Il est important pour l'industrie des produits forestiers de se préoccuper de la réduction des copeaux et des déchets de bois en fines particules. Toutefois, la réduction d'un matériau fibreux en particules de très petites dimensions est difficile et il existe très peu d'équipements capables d'accomplir cette transformation. L'objectif principal de cette étude est de mettre à l'épreuve la broyeuse Szego, broyeuse à anneau-rouleau nouvellement mise au point par l'Université de Toronto et la General Comminution Inc. pour les applications que l'on vient de mentionner.

La majorité des travaux de recherche a été réalisée avec une unité pilote comprenant une alimentation, une broyeuse Szego de 22 cm de diamètre et un dispositif de récupération du produit. On a étudié les effets des vitesses d'alimentation, de fonctionnement et des variables de conception sur la capacité de la broyeuse, la taille des particules produites et la consommation d'énergie. Les principales variables à l'alimentation étaient le type de matériau et sa teneur en humidité. Les principales variables du fonctionnement étaient la vitesse de rotation de la broyeuse ainsi que le nombre de passes nécessaires du matériau dans la broyeuse. Des essais supplémentaires ont été effectués avec une broyeuse industrielle (46 cm) pour obtenir des données sur la conception d'une broyeuse à bois industrielle.

On a pu prouver avec la broyeuse Szego la possibilité technique d'une réduction en particules de moins de 2 000 µm des copeaux verts (bois humide), destinés à la conversion chimique et d'une réduction de pastilles de déchets de bois, de résidus et des écorces en particules de moins de 1 000 µm, destinées à être brûlées en suspension. La dimension des particules diminue avec la vitesse de rotation de la broyeuse et augmente avec la vitesse d'alimentation en matériau. La consommation d'énergie augmente avec la vitesse de rotation et avec la vitesse d'alimentation en

matériau. On a pu établir des relations quantitatives en fonction de la taille des particules et de la consommation d'énergie selon la vitesse de la broyeuse et l'alimentation en matériau pour les copeaux de tremble humides, les pastilles de "Energex" et les résidus de bois provenant des forêts des Grands Lacs broyés avec la broyeuse de 22 cm.

La difficulté du broyage se traduit par un faible degré de réduction de la taille des particules et une forte consommation d'énergie. Dans l'ordre croissant des difficultés de broyage on trouve lors des essais: les déchets de bois en pastilles, les écorces d'épinette noire, les résidus fragmentés provenant du nord de l'Ontario, les copeaux d'épinette humides et les copeaux de tremble humides. Les copeaux de bois très fibreux et résistants sont beaucoup plus difficiles à broyer que les déchets de bois partiellement fibreux.

En général, les matériaux humides sont plus difficiles à broyer que les matériaux secs. Si la teneur en humidité dépasse un certain niveau, selon le type de matériau, la réduction de la taille des particules est limitée par la formation d'agglomérats de fines particules. Dans le cas des déchets de bois qui sont réduits en particules fines pour être brûlés en suspension, le matériau doit être au moins séché à l'air (environ 10 % d'humidité totale) pour permettre un broyage et une combustion efficaces.

Par exemple, des copeaux de tremble humides broyés avec la broyeuse de 22 cm produiront des particules de 2 000 µm (mesurées au tamis à sec) d'une teneur en humidité de 92 % après deux passes, à 1 100 tr/mn et à une vitesse de 170 kg/h (85 kg/h pour du bois étuvé) avec des rouleaux 8/16. La consommation d'énergie est d'environ 340 kWh/tonne (bois sec). Pour les résidus séchés à l'air on obtient des particules de 1 000 µm et à 80 % d'humidité en une passe à 1 000 tr/m, à une vitesse de 365 kg/h avec des rouleaux 8/16. La consommation de l'énergie est de 46 kWh/tonne (bois sec).

La consommation d'énergie de la broyeuse Szego est faible comparée à celle des autres équipements de broyage du bois. Par exemple, une consommation de 1 810 kWh/tonne sèche a été rapportée pour le broyage des copeaux de bois avec une déchiqueteuse à disques (22).

La capacité de la broyeuse de 46 cm était trois ou quatre fois supérieure à celle de la broyeuse de 22 cm pour les particules Energex. Des modifications devraient donc être apportées aux broyeuses de grande dimension de sorte que le rapport de capacité pour les résidus soit similaire.

Il faut maintenant procéder à l'installation et à l'essai de la broyeuse Szego en fonctionnement continu et étudier les applications industrielles de broyage du bois. La broyeuse de 32 cm conçue récemment et installée en plusieurs endroits, serait très appropriée pour le broyage des résidus pour la combustion en suspension, et ceci à une vitesse d'environ 0,5 tonne/h. Une broyeuse de 64 cm capable de broyer les résidus à une vitesse d'environ 2 tonnes/h est à l'étude.

Cette étude est la plus complète réalisée à ce jour concernant le broyage du bois avec une broyeuse Szego. Les résultats des essais effectués sur la broyeuse pilote de dimension réduite sont très encourageants comparés aux résultats d'autres types d'équipement de broyage. D'autres travaux de laboratoire devraient être entrepris avec des broyeuses de 22 cm et 46 cm. Les domaines nécessitant des essais supplémentaires ont été déterminés. Toutefois, il faut maintenant étudier l'installation de ces broyeuses à bois dans l'industrie. Les résultats en laboratoire ont prouvé que cela était possible.

1.0 INTRODUCTION

The importance of the forest products industries to the Canadian economy is difficult to exaggerate. Pulp and paper alone account for approximately 8% of our gross national product (2). It is also difficult to exaggerate the importance of comminution equipment to forest products operators. Pulp manufacturers chip and defibrate wood; power plant operators "hog" wood wastes for combustion; wood flour manufacturers mill wood into small particles for use as fillers; particle board manufacturers mill wood wastes; and sawmills must comminute their residues in order to dispose of them (3).

However, much of the comminution equipment for the above applications produces coarse or medium-sized products. Chippers and flakers produce wood chips and flakes, of the order of 5 cm in size, from logs (4,5). A typical size specification for wood waste produced from hammer hogs is also 5 cm (6). Stone grinders and disk refiners produce a considerably finer product, mechanical pulp, from wood chips, but the grinding processes are wet and the intention is to preserve fibre (wood cell) length, typically 3 mm, for papermaking. The median size of mechanical pulps is of the order of 300 μm when measured by a Bauer-McNett fibre classifier (7,8,9,10). (It should be noted that wood fibre size measurements with this device are about one-third or one-half as large as measurements with dry sieve shakers. See, e.g., data in Ref. 11).

Fine grinding of wood wastes and wood chips is important and will likely become more common as reliable equipment is developed to accomplish the task. Product sizes of less than 1000 μm are required to burn wood wastes in suspension (12). Similar or even smaller sizes, perhaps of the order of 200

μm, may be required for wood chip products (13). These products may be used for chemical conversion, e.g., into fermentation substrate and then ethanol, or for filler used in the manufacture of chipboard. In the past year, General Comminution Inc. (GCI), has prepared wood chip products with the Szego Mill for both of the above applications, by others.

It seems that very few types of mills are available to industry for fine grinding of wood. The prevalent type, at least for grinding wood wastes, is the hammer mill (14,15). A major problem with fine grinding of wood waste with the hammer mill is rapid hammer wear. One industrial installation was shut down because of this problem (16) and another, described by Saunders (15), was reported to be having similar difficulties (17).

Ball milling has been used for fine grinding of wood in the laboratory (18) and, it seems, to some extent in industry (3). The disadvantages of the ball mill are its large size and consequently its low specific capacity (capacity per unit mill volume), and its large energy consumption.

The Szego Mill, a novel ring-roller mill developed by the University of Toronto and GCI, has been proven to be an efficient grinder for various applications (1). Numerous data have been obtained, especially for coal grinding, which demonstrate that the mill has a high capacity and moderate power consumption, and is very cost effective. It was desired to establish, first of all, whether the Szego Mill is capable of grinding wood chips and wood wastes to fine sizes, and then, whether similar benefits would be obtained as for coal grinding. Power consumption values, which are relatively high for wood grinding (of the order of several hundred kilowatt-hours per tonne of oven-dry wood (13,11)), were of particular interest.

It was also desired to add to the scientific knowledge of wood comminution. Very little information about particle size and shape, and the power consumption of wood comminution, is available. This was one of the major reasons for holding the conference at which the above-mentioned paper was presented (3). Particle characteristic and energy consumption data for the Szego Mill and other fine-grinding mills would surely be a contribution.

2.0 OBJECTIVES

The major objective of this study was to establish and begin optimizing the performance of the Szego Mill for grinding wood chips and wood wastes to fine particle sizes. This included establishing and improving the operation of the pilot unit, described in the following section, and the commercial-size mill; obtaining information for the design of industrial wood-grinding units; and collecting data for modelling the performance of the Szego Mill in these applications.

The effects of various feed, operating and mill design variables were to be investigated. The feed variables included the type of material and its moisture content. The operating variables included the mill rotational speed, and the rate of material, number of passes of material and flow rate of air through the mill. The major design variable investigated was the ridge-and-groove pattern of the rollers. The effects of these variables on mill capacity, product particle characteristics, especially size, and power consumption, were studied.

The grinding of two basic types of materials, wood wastes and wood chips, was investigated. Two mill product applications of particular interest

were the combustion of dry pulverized wood waste in a suspension burner, and the conversion of moist, finely-ground wood chips into fermentation substrate, and subsequently, ethanol. Thus it was of prime importance to determine the milling conditions at which the specifications for the respective mill products were met.

As stated above, information was to be obtained for the design of industrial wood-grinding units. This was the primary objective of tests with the commercial-size mill. GCI is planning to test a Szego Mill in a continuous, industrial wood-grinding operation, likely a unit to pulverize wood waste into suspension burner fuel, in the near future.

One additional objective, and not the least, was to gather particle characteristic and energy consumption data to add to the scant scientific knowledge of wood comminution.

3.0 METHOD

3.1 Equipment Used for Test Runs

Most of the tests were done with the wood-grinding pilot unit. Unless otherwise noted, the data presented in this report are from these tests.

A schematic diagram of the pilot unit is shown in Figure 3.1, and photographs of the major pieces of equipment are shown in Figure 3.2. The material to be ground is fed from a hopper with a vibratory feeder, which controls the feed rate to a chute. It falls through the chute into the mill inlet at the top of the mill. The mill is 22 cm in diameter and contains three 30-cm-long grooved rollers, which are driven by a 30 hp electric motor. (A

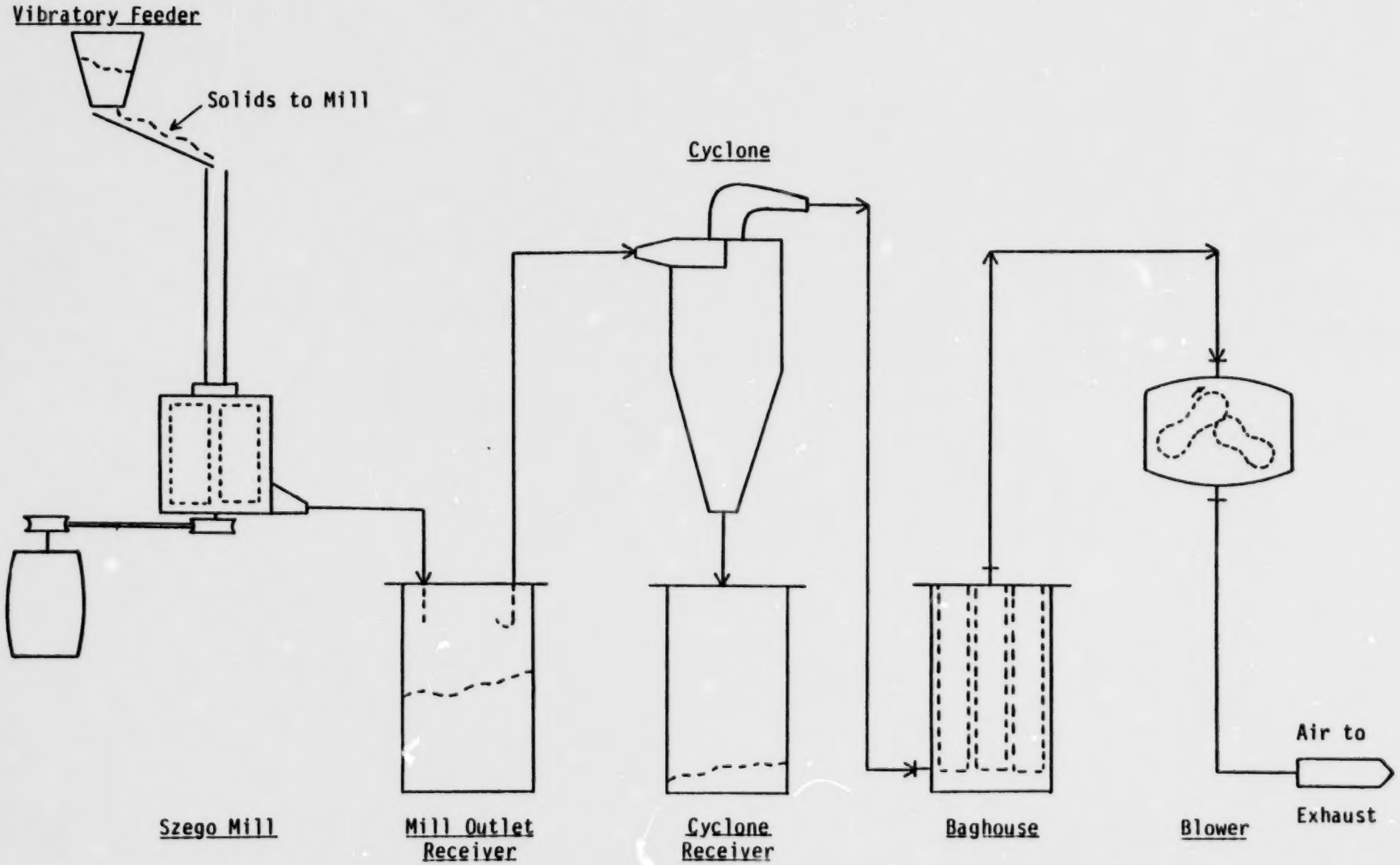
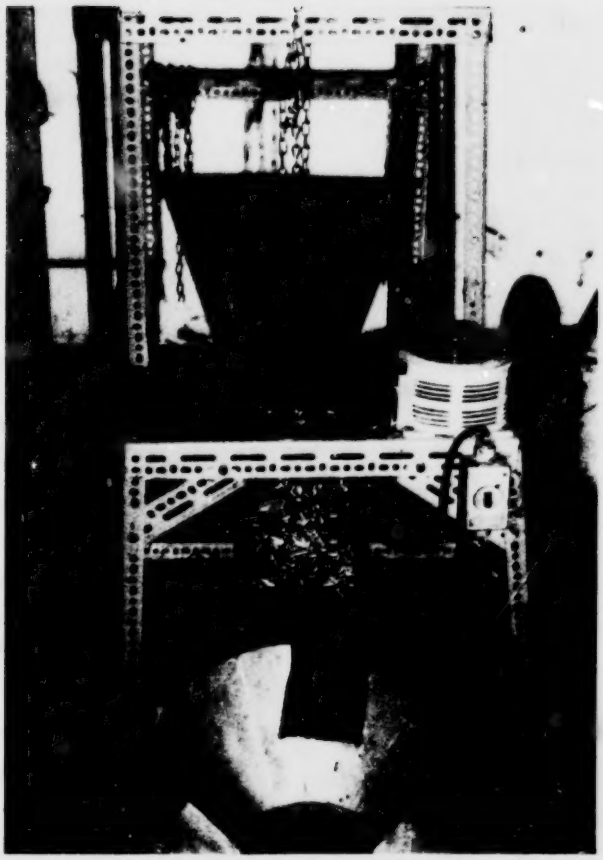


Fig. 3.1 Schematic diagram of wood-grinding pilot unit



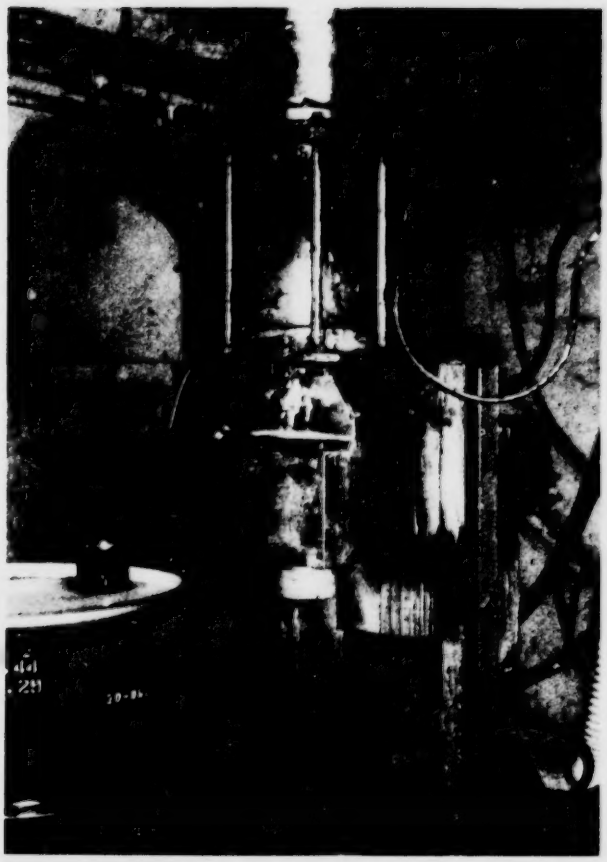


Fig. 3.2 a) Vibratory feeder (top left)
b) Pilot-size (22-cm diameter) Szego Mill: fed from top; discharges to mill outlet receiver; driven by 20 hp motor (top right)
c) Baghouse and 'Aerzen' rotary-lobe blower. Baghouse inlet is from cyclone (not shown).

number of experiments were performed with an identical mill driven by a 20 hp motor). Figure 3.3, a schematic diagram of the mill, shows how it operates.

The material passes through the mill, where it is ground, and is then conveyed pneumatically from the mill discharge, at the bottom of the mill, into the mill outlet receiver, where most of it is collected. Dusty air from the first receiver enters the cyclone. Almost all of the remaining solids are collected in the cyclone receiver. Air from the cyclone, which contains only trace amounts of very fine dust, passes through the baghouse and then to the rotary-lobe blower. The blower pulls air through the mill and the collection system and discharges it to an atmospheric exhaust duct.

A number of tests were done with the commercial-size mill. This mill is 46 cm in diameter and contains eight 46-cm-long rollers, driven by a 75 hp electric motor. The equipment configuration was the same as for the pilot unit tests. A screw feeder was used in place of the vibratory feeder, and the product collection system of the pilot unit was borrowed.

3.2 Methods of Obtaining Data

The mill rotational speed was measured with a tachometer. The tachometer is very accurate, to within several rpm, and, once set, the mill speed is virtually constant.

The average production rate was determined by timing the length of a pass through the mill, typically 3 minutes, and weighing the collected product. The product rate is not equal to the feed rate because moisture is evaporated during grinding. Obviously, this is more pronounced when moist materials, containing up to about 50 wt% total moisture, are ground. Also, use of the average product rate compensates for fluctuations in the feed rate.

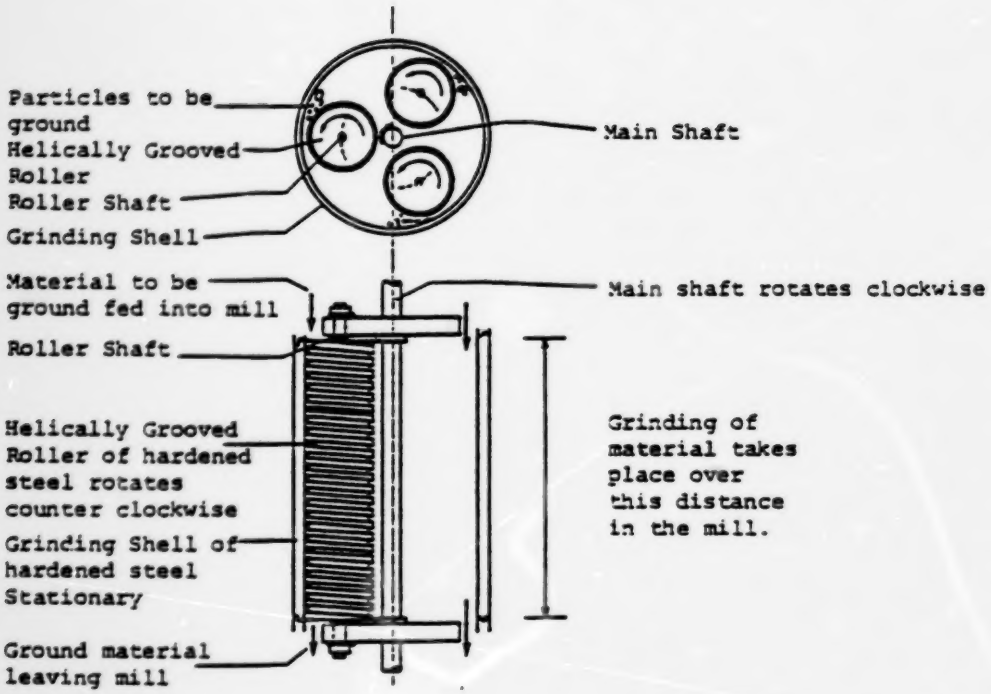

Particles to be ground
Helically Grooved Roller
Roller Shaft
Grinding Shell
Main Shaft
Material to be ground fed into mill
Main shaft rotates clockwise
Roller Shaft
Helically Grooved Roller of hardened steel rotates counter clockwise
Grinding Shell of hardened steel Stationary
Grinding of material takes place over this distance in the mill.
Ground material leaving mill

Fig. 3.3 Schematic diagram of the Szego Mill

These were troublesome when feeding moist, broken, fibrous materials, e.g., intermediate wood chip products, with the vibratory feeder. Blockages tended to form at the bottom of the feed hopper (see Figure 3.2a). These were avoided by having an operator tend the feeder. The screw feeder, used for tests with the commercial-size mill, operates with little fluctuation but is unsuitable for testing small batches of material.

Size analysis began with a careful sampling procedure, especially for the dry materials, which contained a large proportion of fine particles. A large sample was obtained from several locations in the collected product, and then carefully split into a smaller sample for sieving. The seiving was done for 30 minutes with a 'Ro-Tap' Testing Sieve Shaker. This method, which employs a vertical nest of sieves, is a standard dry-seiving method. It was used for determining the particle-size distributions of all samples, including those of moist materials. It should be noted that all the tests performed, even those with moist materials, were "dry" grinding tests: no water was added.

The sieving procedure is very precise for wood-particle sizes down to approximately 100 μm. Particles smaller than this did not form a major fraction of the products desired in these tests. When sieve analyses were repeated the precision of the cumulative particle-size distribution was within a fraction of one percent, producing essentially the same curve when the distribution was replotted. However, as mentioned in the introduction, particle size results may vary considerably from one method to another. This underscores the importance of using standard methods and good technique.

Particle shapes were observed qualitatively by inspecting particles in the sieved fractions of the different types of materials, and also from photographs of these fractions.

Initially, moisture content was determined by weighing a sample, placing it in an oven at 104°C, and reweighing it periodically until it reached a constant weight. The moisture content of the sample is the difference in mass. This procedure was very similar to one of the standard procedures described in Fengel and Wegener (19). It is accurate to within 0.1 wt% total moisture or less.

The disadvantage of this method is that it takes a long time, up to about 8 hours for moist materials with large particles, e.g., moist bark. Subsequently, a moisture balance, which employs a heat lamp, was used. Results with the moisture balance were compared for the different types of materials and found to be virtually identical, and analysis times were reduced to the order of one half-hour.

It was found that moisture loss from sample bags containing moist materials occured over a period of weeks. Thus it was important to analyze the moisture contents of such materials soon after sampling has been done.

Power consumption was calculated from measurements of the current drawn by the electric motor which drives the mill. The time-averaged current was derived from measurements made at regular intervals with a digital ammeter. Continuous chart recordings of amperage were also made for a number of runs.

The power output of the motor, which is the power consumed by the mill and drive, was calculated from the time-averaged current values using the manufacturer's power output and amperage data, corrected for the average measured line voltage. It is estimated that the power consumption values are

accurate to within 10 to 15%. The consistency of the results from series of tests with different materials shows that the precision is good.

4.0 RESULTS AND DISCUSSION

4.1 Grinding of Wood Chips

4.1.1 Introduction

Tests were made with aspen chips and spruce chips, using the pilot mill. These materials are moist or "green", containing about 50 wt% total moisture. Because they are moist and fibrous, they behave quite differently from dry wood wastes when being handled and milled. The ground chip products were to be used as feed to an acid hydrolysis unit in a wood-to-ethanol pilot plant operated by others. The specification for this application was that essentially all (97 wt%) of the product could pass through a 2000-µm screen. Another potential application for ground wood chips is as a filler in chipboard, a "manufactured lumber". The Department of Forestry at the University of Toronto has manufactured some chipboard using wood flour made with the Szego Mill.

4.1.2 Aspen Chip Grinding

Most of the experiments with wood chips were done with aspen. Aspen chips are of the order of 2 cm by 2 cm by 3 mm in size and contain approximately 50 wt% total moisture. A sample of aspen chips is shown in Figure 4.1.

In the experiments with aspen, mill rotational speeds in the range of 700 to 1200 rpm were used. Runs were made with product rates up to about 300 kg/h. It should be noted that the product rates in this report are total rates

Fig. 4.1 Aspen Chips

of material, including moisture, not rates of oven-dry wood. (For dry materials, e.g., wood wastes, there is obviously little difference between the two.) Generally 2 passes through the mill were made. There was usually no net size reduction after the second pass because of the formation of agglomerates from small fibre bundles produced in the first and second passes. This phenomenon is discussed in more detail below. Two sets of rollers were used. Both had 8-mm square ridges, but one set had 8-mm-wide grooves while the other had 16-mm-wide grooves.

The results of the runs with 8/16 rollers are summarized in Tables A.1 and A.2 of the Appendix. A typical set of results for aspen grinding, from Run 36, is presented in Table 4.1, alongside typical sets of results from the grinding of hog fuel and pelletized wood waste. From this table it is quite evident that grinding moist aspen chips is a more difficult task than grinding dry wood wastes: the degree of size reduction is lower and the power required is higher. The particle-size distributions of the mill products and the final, classified product from Run 36 are shown in Figure 4.2. Samples of first and second pass products and their fractions from Run 36 are shown in Figures 4.3 and 4.4, respectively. Since the size intervals and the scale are the same in Figures 4.3, 4.4, 4.13, 4.14, 4.24, and 4.25, the product characteristics of moist aspen chip comminution may be compared to those of wood pellet and hog fuel comminution.

Typically, the product specification for hydrolysis (97 wt% passing 2000 µm), was met after two passes using 8/16 rollers, at 1100 or higher rpm, with a product rate of the order of 170 kg/h, followed by classification with a 4750-µm vibrating screen. The second-pass products from runs with 8/16 rollers at 1100 and 1200 rpm averaged 91.8 wt% passing 2000 µm. By classifying with

Table 4.1

Typical Sets of Results for GLFP Hog Fuel, 'Energex' and Aspen Grinding Runs

	GLFP Hog Fuel (Run 60)	'Energex' (Run 52)	Aspen (Run 36)
Total Moisture Content of Feed:	8.3 wt%	7.0 wt%	50 wt% (approx.)
Mill Speed:	1000 rpm	1000 rpm	1100 rpm
No. of Passes:	1	1	2
Product Rate(s):	376 kg/h	323 kg/h	188 & 190 kg/h
Roller Type:	8mm/8mm	8mm/8mm	8mm/16mm
Product Median Size(s):	405 µm	355 µm	1020 & 930 µm
Product 80%-Passing Size(s):	1040 µm	815 µm	2220 & 1580 µm
Total Power Consumption:	15.7 kW	13.6 kW	15.0 & 14.6 kW
Total Specific Energy Consumption:	46 kWh/T ODW	45 kWh/t ODW	150 & 140 kWh/t ODW

Note: Product rates, product sizes and power consumption values for Run 40 are for the 1st and 2nd passes, respectively.

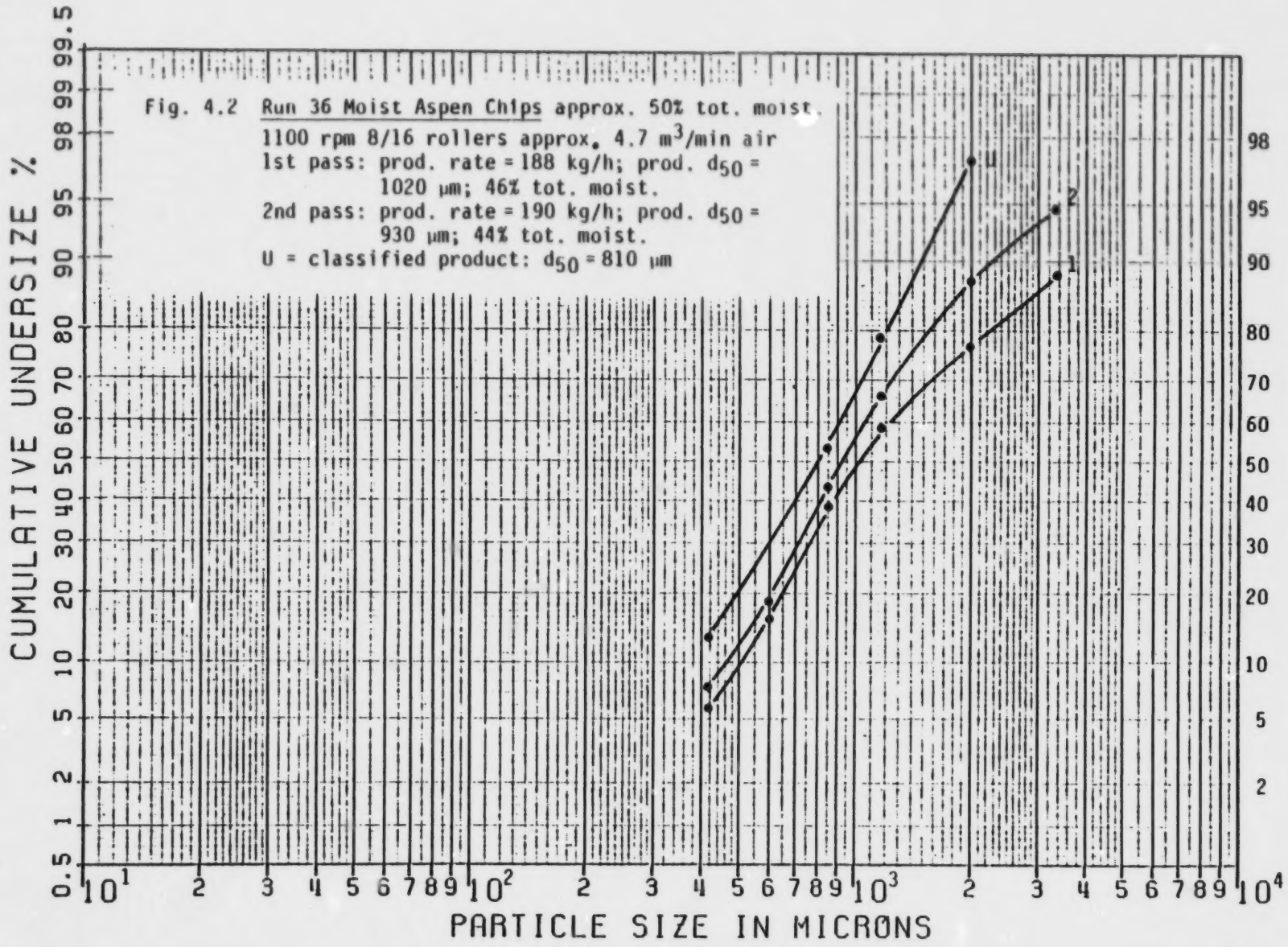
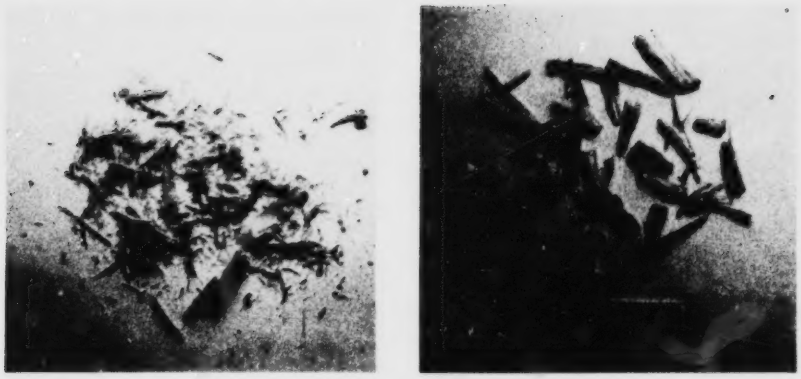


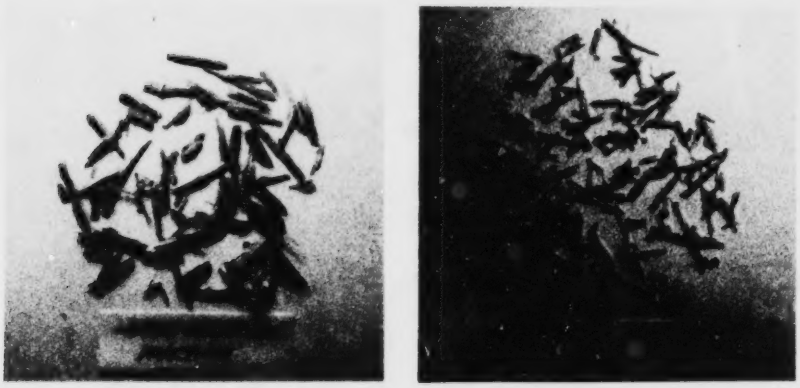
Fig. 4.2 Run 36 Moist Aspen Chips approx. 50% tot. moist.
1100 rpm 8/16 rollers approx. 4.7 m³/min air
1st pass: prod. rate = 188 kg/h; prod. d50 = 1020 µm; 46% tot. moist.
2nd pass: prod. rate = 190 kg/h; prod. d50 = 930 µm; 44% tot. moist.
U = classified product: d50 = 810 µm
U
2
1
CUMULATIVE UNDERSIZE %
0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.5
98 95 90 80 70 60 50 40 30 20 10 5 2
10¹ 2 3 4 5 6 7 8 9 10² 2 3 4 5 6 7 8 9 10³ 2 3 4 5 6 7 8 9 10⁴
PARTICLE SIZE IN MICRONS

Total



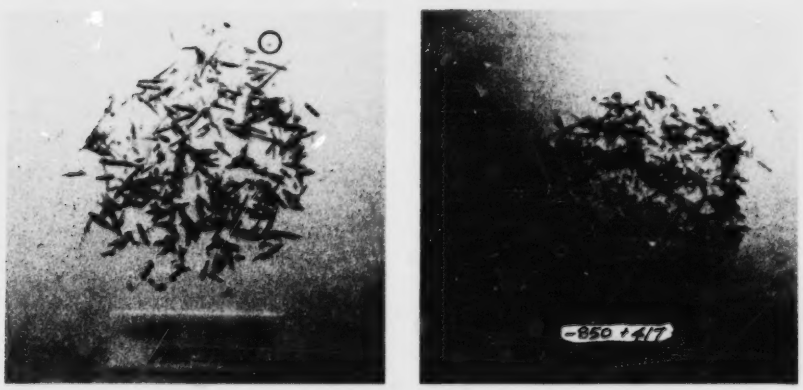
7.4 wt%

12.3 wt%



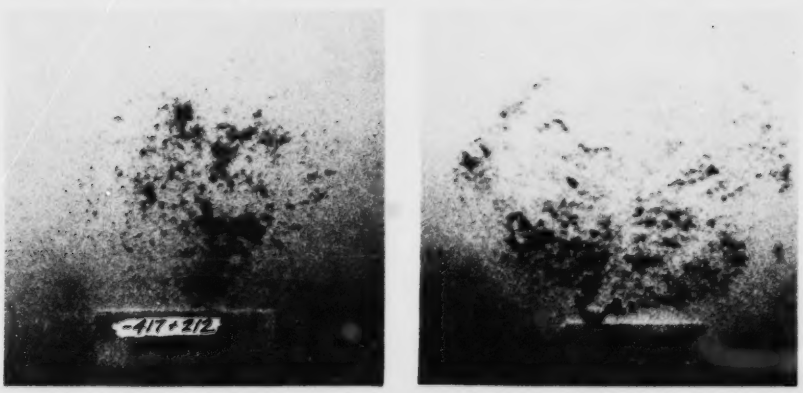
14.2 wt%

11.6 wt%



27.9 wt%

18.5 wt%



8.1 wt%

Fig. 4.3 Moist Aspen Run 36 1st pass product and its size fractions
Notes: Percentages indicate relative amounts.
Photographs and percentages for dry sample.

Total

5.1 wt%

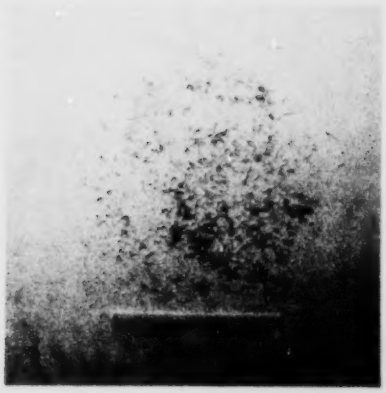
7.4 wt%

16.5 wt%

14.9 wt%

27.4 wt%

18.2 wt%



10.5 wt%

Fig. 4.4 Moist Aspen Run 36 2nd pass product and its size fractions
Notes: Percentages indicate relative amounts.
Photographs and percentages for dry sample.

the vibrating screen an average of about 7% of the mill product, with a median size of the order 3500 µm, was rejected to the oversize fraction.

Comparison of product sizes for 8/16 rollers and 8/8 rollers at the same mill speeds reveals that the 8/16 rollers perform better despite having less grinding surface. For example, the second-pass product from a run with 8/8 rollers at 1100 rpm (Run 20) had only 81.8 wt% passing 2000 µm, compared to an average of 91.8% with 8/16 rollers. The reason for the inferior performance of the 8/8 rollers is that virtually all of the grooves, which are square and relatively narrow, became completely clogged, mostly with aspen "pulp", after only two or three runs. In contrast, only the top one or two grooves of the 8/16 rollers became clogged, mostly with large chip fragments.

The decrease in product particle size with increasing mill rotational speed is indicated in Figure 4.5, in which the first pass median size for 8/16 rollers is plotted against rotational speed. A speed of approximately 1100 rpm appears to be the best compromise between meeting the product size specification and prolonging the life of the mill bearings.

In Figure 4.6, first pass product size for 8/16 rollers is plotted against product rate with rotational speed as a parameter. Product size increases with production rate and decreases with rotational speed. Product rates ranged from about 80 to 270 kg/h, with most in the range of 150 to 190 kg/h. The relationships expected for 1000, 1100, 1200 rpm are shown.

4.1.3 Effects of Moisture Content on Aspen Grinding

It was anticipated that the grinding of dry aspen chips would be markedly superior to that of moist chips. In addition, the large problems of

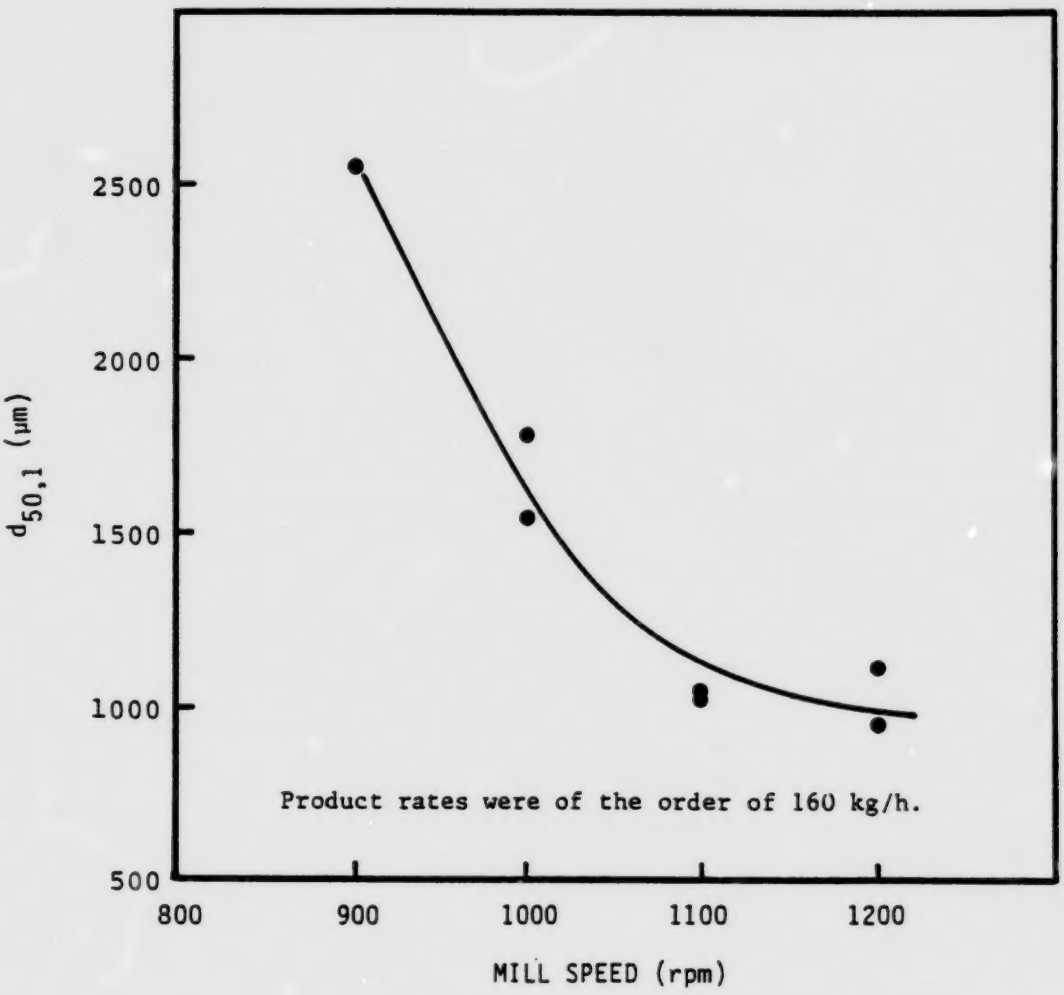


Fig. 4.5 Moist Aspen Grinding with 8/16 Rollers
1st Pass Product Median Size vs Rotational Speed

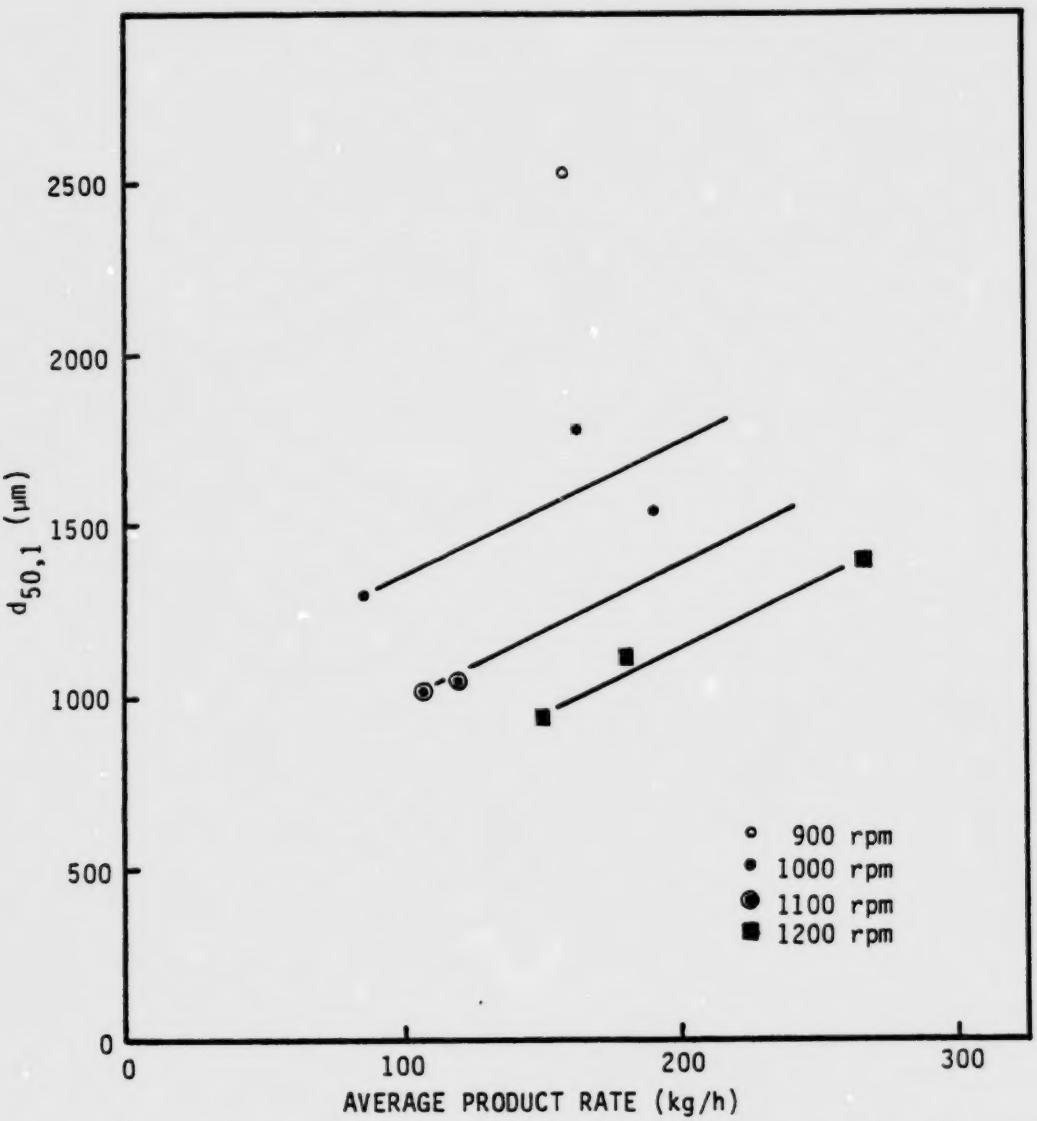


Fig. 4.6 Moist Aspen Grinding with 8/16 Rollers
1st Pass Product Median Size vs Product Rate

handling moist fibrous material would be avoided. While, in practical applications, the drying operation may not be economical, a couple of tests with air-dried aspen were nevertheless carried out.

Many benefits are also foreseen for wet grinding, i.e., grinding with water added continuously to the mill. However, for the wood-to-ethanol application, it was felt that, as a result of the increase in distillation cost to separate ethanol from dilute solution at the end of the process, only 1 kg of water could be added per kg of chips. This would require the production of a 25% consistency "paste", if such an operation were possible.

Early in 1985, Imanudin, who carried out the first studies of wood grinding with the Szego Mill (20), performed some successful tests in which he produced 16% ground aspen slurry in one pass. The size analysis of this material is not available, but clearly the product was much finer than the first-pass product from dry grinding of moist or dry aspen chips. It was not possible, however, to produce a 25% "paste". Perhaps wet grinding followed by mechanical water removal and/or drying with flue gas may prove to be more efficient for grinding moist chips.

Most of the tests were done with moist (approximately 50% moisture) aspen chips. For comparison, the results of several runs with moist aspen chips, using 8/8 rollers, are summarized together with the results of similar runs with air-dried aspen chips in Table A.3, in the Appendix. In general, after the second pass, moist product is coarser than dry product, and moist chip grinding consumes more power than dry chip grinding.

The product particle-size distributions for two of the above runs, Run 16 (moist) and Run 24 (air-dried), are shown in Figures 4.7 and 4.8, respectively. In Figure 4.7, the limit of size reduction of moist material,

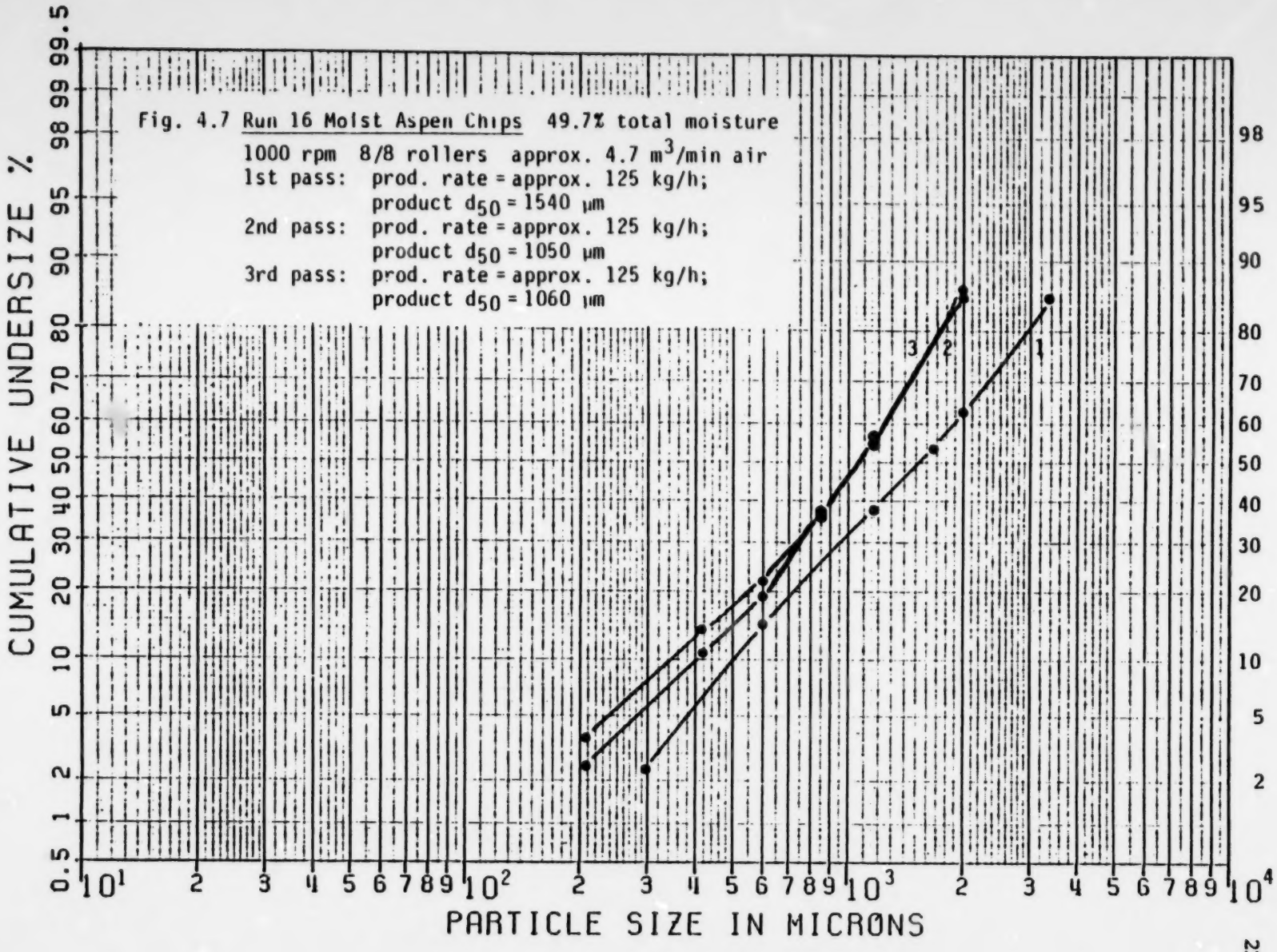


Fig. 4.7 Run 16 Moist Aspen Chips 49.7% total moisture
1000 rpm 8/8 rollers approx. 4.7 m³/min air
1st pass: prod. rate = approx. 125 kg/h;
product d50 = 1540 µm
2nd pass: prod. rate = approx. 125 kg/h;
product d50 = 1050 µm
3rd pass: prod. rate = approx. 125 kg/h;
product d50 = 1060 µm
CUMULATIVE UNDERSIZE %
0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.5
98 95 90 80 70 60 50 40 30 20 10 5 2
3 2 1
10¹ 2 3 4 5 6 7 8 9 10² 2 3 4 5 6 7 8 9 10³ 2 3 4 5 6 7 8 9 10⁴
PARTICLE SIZE IN MICRONS

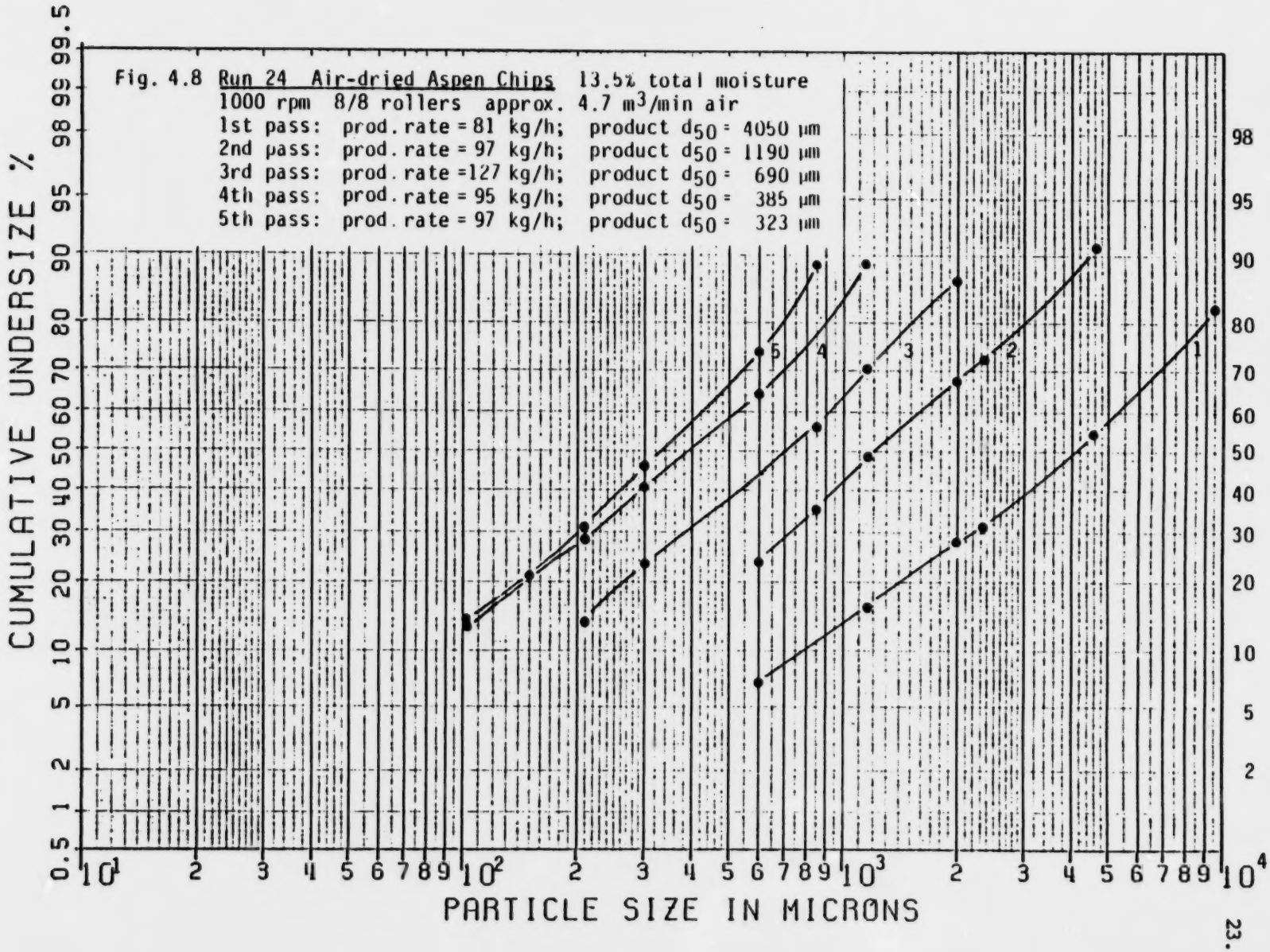


Fig. 4.8 Run 24 Air-dried Aspen Chips 13.5% total moisture
1000 rpm 8/8 rollers approx. 4.7 m³/min air
1st pass: prod. rate = 81 kg/h; product d50 = 4050 µm
2nd pass: prod. rate = 97 kg/h; product d50 = 1190 µm
3rd pass: prod. rate = 127 kg/h; product d50 = 690 µm
4th pass: prod. rate = 95 kg/h; product d50 = 385 µm
5th pass: prod. rate = 97 kg/h; product d50 = 323 µm
CUMULATIVE UNDERSIZE %
0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.5
PARTICLE SIZE IN MICRONS
10¹ 2 3 4 5 6 7 8 9 10² 2 3 4 5 6 7 8 9 10³ 2 3 4 5 6 7 8 9 10⁴
1
2
3
4
5

which results from the formation of agglomerates of fine particles, is very evident. There is almost no difference between the particle-size distributions of the second- and third-pass products. This is typical behaviour for moist wood chips ground at 1000 or higher rpm. At less than 1000 rpm, it was found that more passes can be made before the limit is reached, but the final product is considerably coarser than at higher mill speeds.

A few agglomerates are present in the first pass product of Run 36 (1100 rpm), particularly in the 850 to 1168 μm fraction (see the circled particulate mass at the 1 o'clock position in Figure 4.3). Many more appear in the second-pass product (see Figure 4.4), particularly in the 1168 to 2000 μm and 850 to 1168 μm fractions. The agglomerates do not seem to appear below 417 μm. Some very large agglomerates were formed, e.g., the particulate mass at 6 o'clock in the +3350 μm fraction in Figure 4.4.

No agglomerate-formation limit to size reduction was encountered in the grinding of air-dried aspen after 5 passes in Run 24 (see Figure 4.8 and Table A.3) or after 7 passes in Run 26 (Table A.3). However, it was discovered that the initial size reduction was better for moist chips than for dry chips, e.g., in Run 16 (moist, Figure 4.7), the median sizes of the products from the first, second and third passes were 1540, 1050 and 1060 μm, respectively, while in Run 24 (dry, Figure 4.8), they were 4050, 1190, and 690 μm. Thus it was not until the third pass that the dry product size was less than the moist. The reason for this surprising behaviour is that during the initial passes through the mill, the dry aspen chips fractured but did not readily break up into small fragments. This indicates that it would be more effective to grind moist chips in the first pass, dry the product, and then grind dry product, than to grind moist material in two consecutive passes.

4.1.4 Particle Characteristics of Ground Aspen

Wood consists of many fibres (cells) of the order of 2 mm long and with an aspect (length-to-diameter) ratio of about 100 (19). These fibres are bound together in a matrix so that most of them are oriented parallel to the axis of the tree stem. This is especially true of coniferous species.

It is well known that wood is stronger across the grain than parallel to it. Thus it is not surprising that, when wood chips are comminuted in the Szego Mill, they tend to break in the direction parallel to the fibres, rather than across them. Flattened fibre bundles with an aspect ratio of about 4 are formed. These are readily seen in the larger size fractions in Figure 4.3. Fibre bundles are found even in the smallest (-212 μm) size fraction.

As described in the previous section, when moist wood chips are ground, not only are the chips broken parallel to and across the fibre axis, but agglomerates are formed. These agglomerates consist of many small fibre bundles compressed together. Most likely they are bonded together by moisture. The agglomerates are most numerous in the 850 to 1168 μm fraction of second- and subsequent-pass products. They resemble pancakes in shape.

4.1.5 Power Consumption for Aspen Grinding

The power consumption for moist aspen grinding with 8/16 rollers is summarized in Table A.2. Power consumption is plotted against product rate, with mill speed as a parameter, in Figure 4.9, and against mill speed for a constant product rate in Figure 4.10. As expected, the power demand increases as the product rate and the mill rotational speed are increased. In general, the power required for grinding wood chips is greater than that for wood

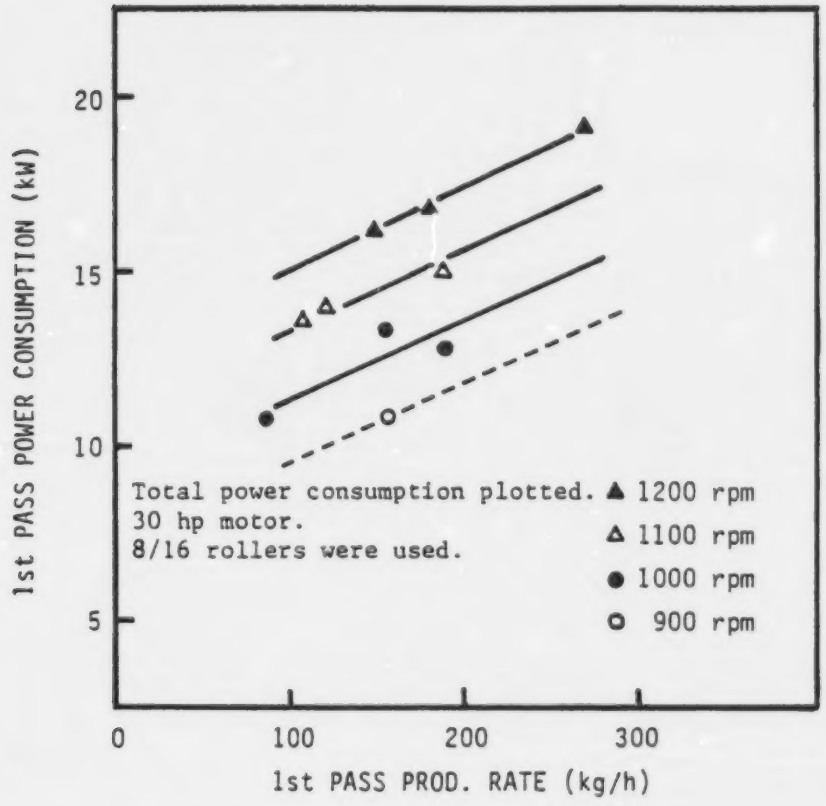


Fig. 4.9 Power Consumption vs Product Rate for Moist Aspen Chips

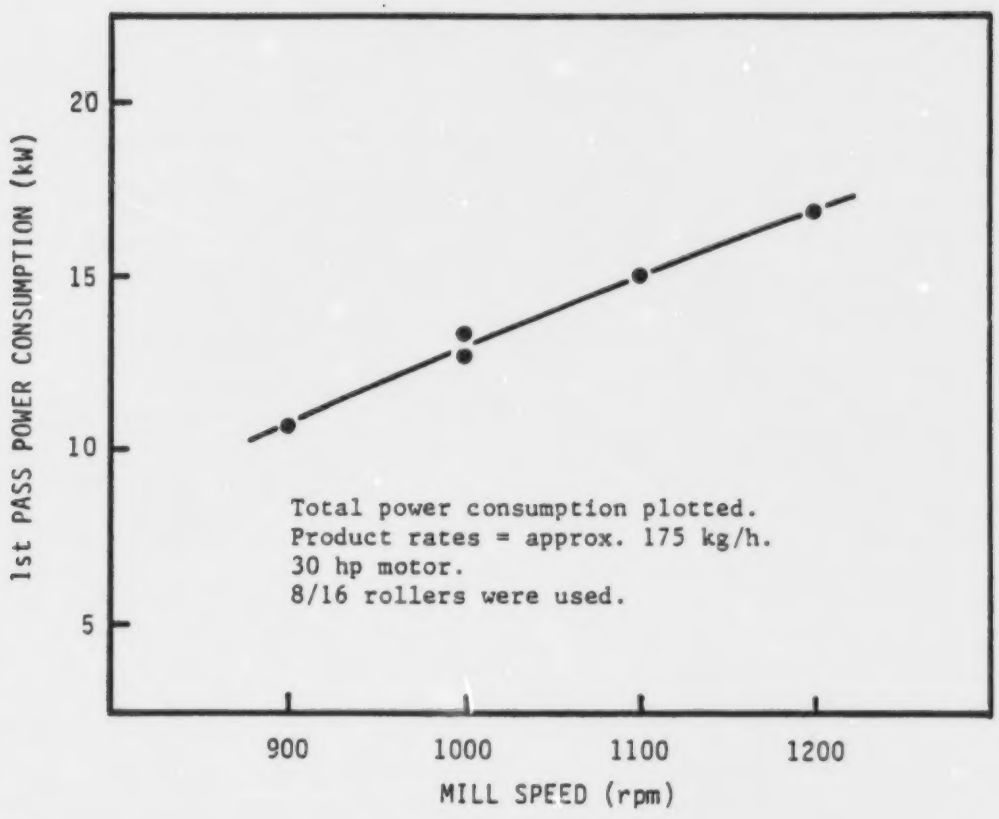


Fig. 4.10 Power Consumption vs Mill Speed for Moist Aspen Chips

wastes (see Table 4.1), and the power required for grinding moist chips is greater than that for dry chips (see Table A.3).

Most of the energy consumed by any grinding mill ends up heating the product and the surrounding environment (21). When moist material is ground, a substantial part of the mill input energy may be spent evaporating moisture. Typically, 10% of the moisture in the feed was evaporated in the first pass, and 5% was evaporated in the second pass, when moist aspen chips were ground. The rate of heat input required to evaporate moisture is approximately 40% of the total power input to the mill for the two passes.

4.1.6 Comparison with Other Types of Comminution Equipment

Some comparisons have been made between the performance of the Szego Mill in grinding moist aspen chips, and the performance of other types of equipment in similar applications. The particle-size distribution of moist aspen product from a Sprout-Waldron laboratory disk refiner was analyzed using a 'Ro-Tap' Testing Sieve Shaker in the same manner that Szego Mill products were analyzed. The laboratory refiner product was coarser than the coarsest Szego Mill second-pass product: only 50% of the former passed a 2000-μm sieve, compared to 74% of the latter and 93.5% of the best (Run 37) Szego Mill product. The energy consumption (kWh/tonne of oven-dry wood) of the laboratory refiner could not be measured, but, based on occasional ammeter readings, it appeared to be quite high.

A brief literature survey was made in an attempt to compare the size reduction and power consumption of industrial wood comminution equipment with that of the Szego Mill. At first it appeared that the pilot-size Szego Mill equipped with 8/16 rollers consumes several times less energy while producing

particles that are several times as large as those produced by an industrial disk refiner. Kano et al (22) report that the production of refiner mechanical pulp with a median size of 250 µm, from Western hemlock chips, required 1810 kWh/tonne ODW. Run 37 Szego Mill second-pass product had a median size of 930 µm (analyzed with the 'Ro-Tap' sieve shaker), and required a total of 440 kWh/tonne ODW for the two passes. However, it is likely that the particle-size distribution of the mechanical refiner product was analyzed with a 'Bauer and McNett' classifier or similar instrument, which gives much finer values than the 'Ro-Tap' sieve shaker.

Hemingway et al (11) have published some data which may be compared to results with the Szego Mill. They studied the grinding of Southern U.S. hardwoods with a screw-extruder comminution device. When "green" red oak chips were ground with an energy consumption of 375 kWh/tonne ODW (19.0 HPD/OD ton), the product median size was 1120 µm as determined by dry screening, and 340 µm as determined with the 'Bauer-McNett' classifier. For Run 37 with the Szego Mill, the first-pass product had a median size of 1020 µm (determined by dry screening) and the specific energy consumption was 230 kWh/tonne ODW. Although different types of wood chips were ground in each case, it does appear that the Szego Mill consumes substantially less energy to grind wood chips to a similar size.

4.1.7 Spruce Chip Grinding

A few experiments were performed with moist and dry spruce chips. The results are summarized in Table A.4. In general, they are similar to those of aspen grinding. Spruce chips are somewhat more grindable than aspen chips:

at similar operating conditions, the particle sizes of spruce products were smaller and the power consumption was lower.

4.2 Grinding of Wood Wastes

4.2.1 Introduction

In recent years, the forest products industries have made efforts to reduce fuel oil consumption by burning wood wastes (14). One of the most desirable ways of doing this is to use a suspension burner. Since wood wastes usually contain a substantial fraction of large particles (of the order of 1 cm to 10 cm in size), a system for pulverizing the wood waste is necessary.

The wood wastes tested with the Szego Mill include pelletized wood waste, hog fuel, which consists primarily of bark, and bark itself. The ground product is to be suitable for combustion in a suspension burner, so the grinding specification is that at least 80 wt% of the product can pass through a 1000-μm screen (12). Most of the experiments with wood wastes have been with 'Energex' pelletized wood waste and Great Lakes Forest Products (GLFP) hog fuel.

4.2.2 Energex Grinding

'Energex' is pelletized wood waste. Apparently, sawdust and shredded bark are mixed, dried and extruded to form pellets. These pellets are approximately 0.6 cm in diameter and 1 cm long (see Figure 4.11a), consist of both fibrous and nonfibrous components, and contain about 7 wt% total moisture.

In the tests with Energex, mill rotational speeds in the range of 700 to 1200 rpm were used. Runs were made with product rates up to and over 800 kg/h.

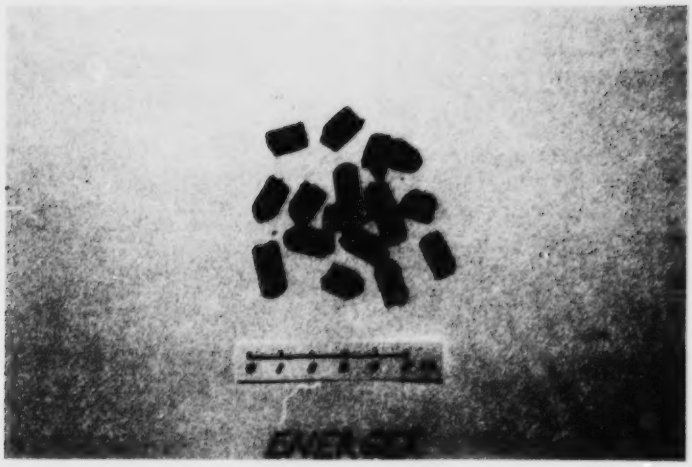


Fig. 4.11a 'Energex' pellets

Fig. 4.11b Air-dried GLFP Hog Fuel

Although the objective was to meet the size specification in 1 pass, usually 2 or 3 passes through the mill were made in order to study the grinding characteristics of the material. Both the 8/8 and 8/16 rollers were used. All the tests were done with pellets containing about 7% moisture, since a dry product is desired, and grinding performance decreases as moisture content is increased, unless very large quantities of moisture are added (wet grinding).

The results of runs with 8/8 rollers and with 8/16 rollers are summarized in Table A.5. In Table 4.1, a set of results for a typical Energex-grinding run (Run 52) is presented alongside corresponding sets of results from the grinding of GLFP hog fuel and moist aspen chips. The particle-size distributions of the products from Run 52 are shown in Figure 4.12. Samples of first- and second- pass products and their fractions from Run 52 are shown in Figures 4.13 and 4.14, respectively.

From Table A.5 it can be seen that the grinding specification is easily met. A typical set of conditions which meet the specification in one pass might be 800 rpm with a product rate of 400 kg/h, using 8/8 rollers. The mill speed required to make specification product depends on the throughput of material. Some data which indicate the nature of this relationship for wood wastes are presented in Table 4.2. Since optimization of the milling operation might be defined simply as the determination of the minimum mill rotational speed, and thus the minimum power required, to meet the size specification at a given product rate, such data are important.

As expected, product particle size decreases as the mill rotational speed increases. This is indicated by the data of Table A.5 and shown in Figure 4.15, for 8/8 rollers. From comparing product particle sizes, e.g., at 1000 rpm, in Table A.5, it can also be seen that 8/8 rollers grind Energex to

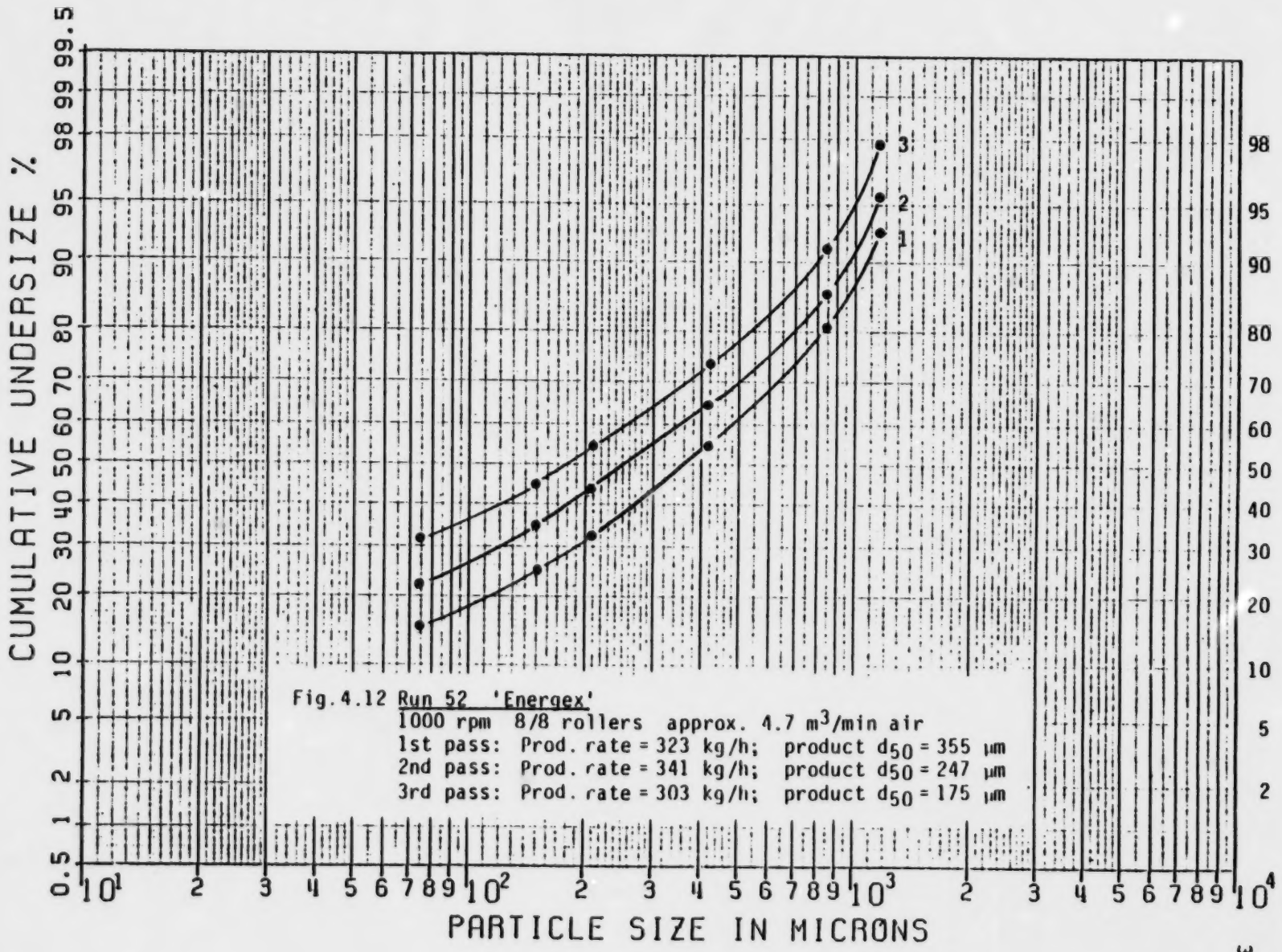
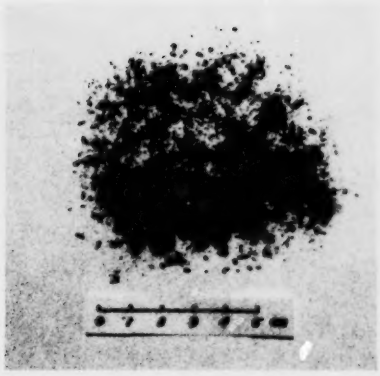


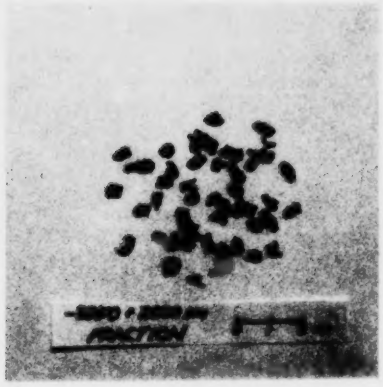
Fig. 4.12 Run 52 'Energex'
1000 rpm 8/8 rollers approx. 4.7 m^3/min air
1st pass: Prod. rate = 323 kg/h; product d_{50} = 355 µm
2nd pass: Prod. rate = 341 kg/h; product d_{50} = 247 µm
3rd pass: Prod. rate = 303 kg/h; product d_{50} = 175 µm

Total

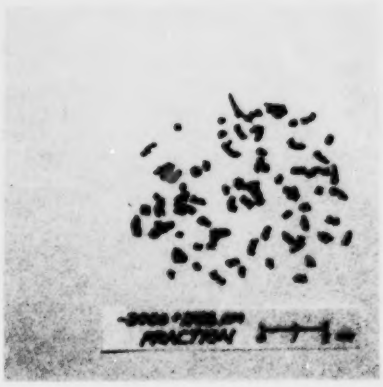


< 0.1 wt%

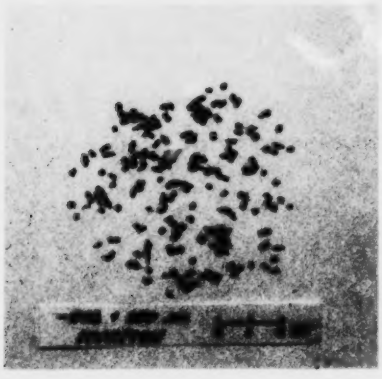
0.5 wt%



6.3 wt%



10.2 wt%



26.6 wt%

22.7 wt%

33.7 wt%

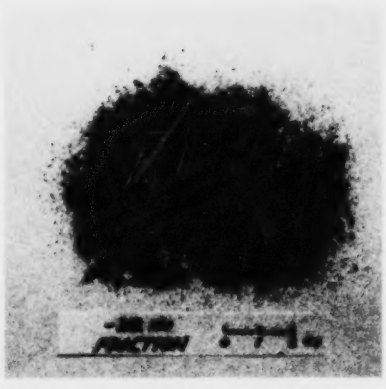
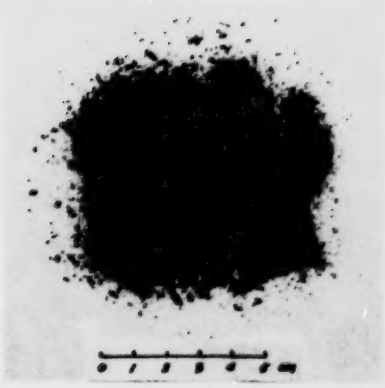


Fig. 4.13 'Energex' Run 52 1st pass product and its size fractions
Note: Percentages indicate relative amounts.

Total



< 0.1 wt%

0.3 wt%

4.2 wt%

7.6 wt%

20.3 wt%

20.3 wt%

47.3 wt%

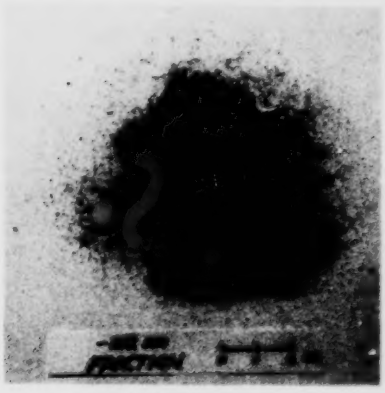


Fig. 4.14 'Energex' Run 52 2nd pass product and its size fractions
Note: Percentages indicate relative amounts.

Table 4.2

Maximum Product Rate at Which Size Specification for Wood Waste Grinding is Met.

Material	Mill Speed (rpm)	Max. Product Rate (kg/h)
GLFP Hog Fuel	1100	400
GLFP Hog Fuel	1000	365
GLFP Hog Fuel	900	250
GLFP Hog Fuel	800	150 (est'd)
GLFP Hog Fuel	750	75 (est'd)
Energex	1100	600 (est'd)
Energex	1000	500
Energex	800	400 (est'd)
Masson bark	1000	500

Notes: Size specification for suspension burning is 80 wt% less than 1000 μm. The above data are for the pilot-size (22-cm diameter) Szego mill with 8/8 rollers.

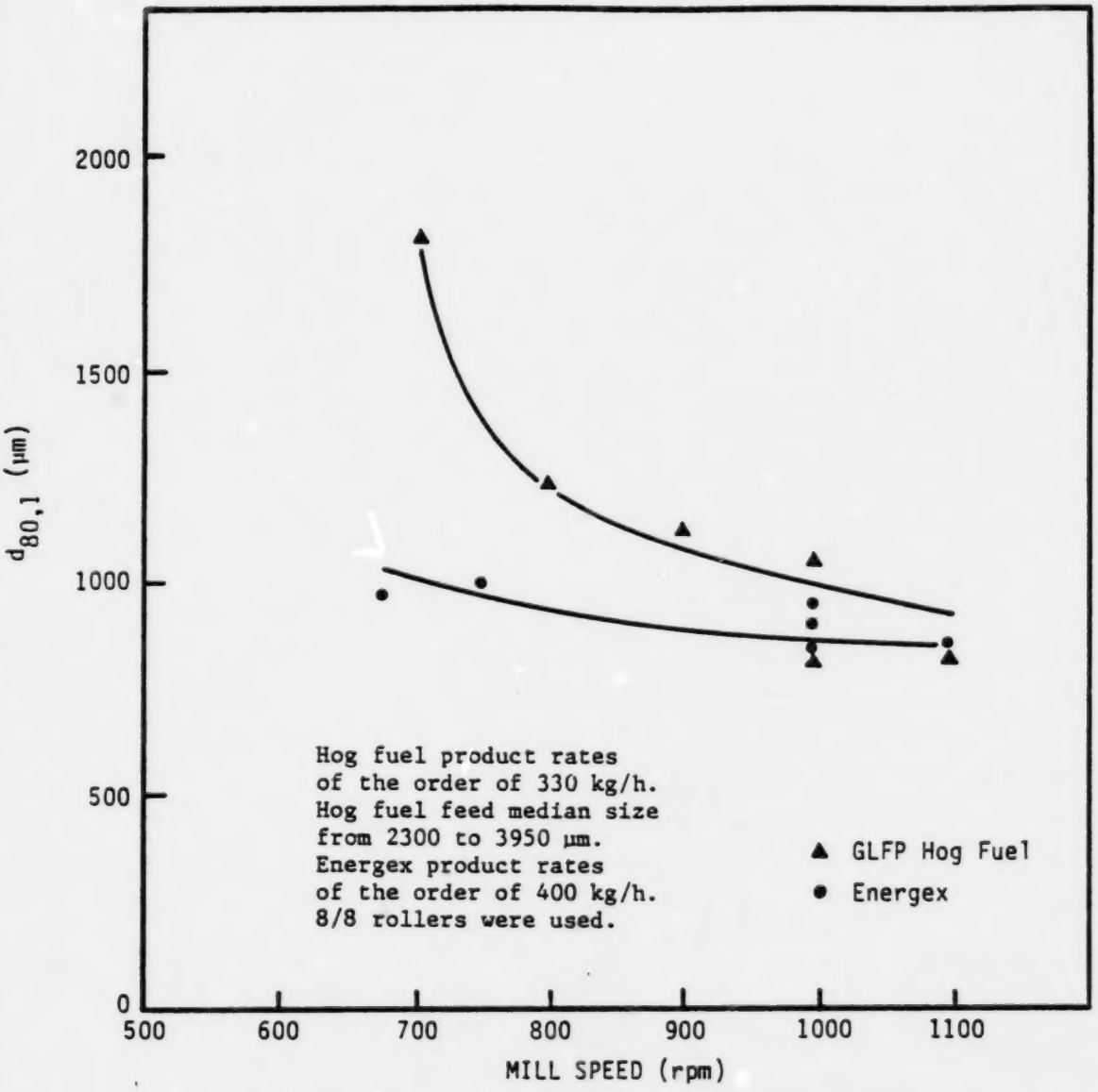


Fig. 4.15 1st Pass Product 80%-passing Size vs Mill Speed for GLFP Hog Fuel and 'Energex'

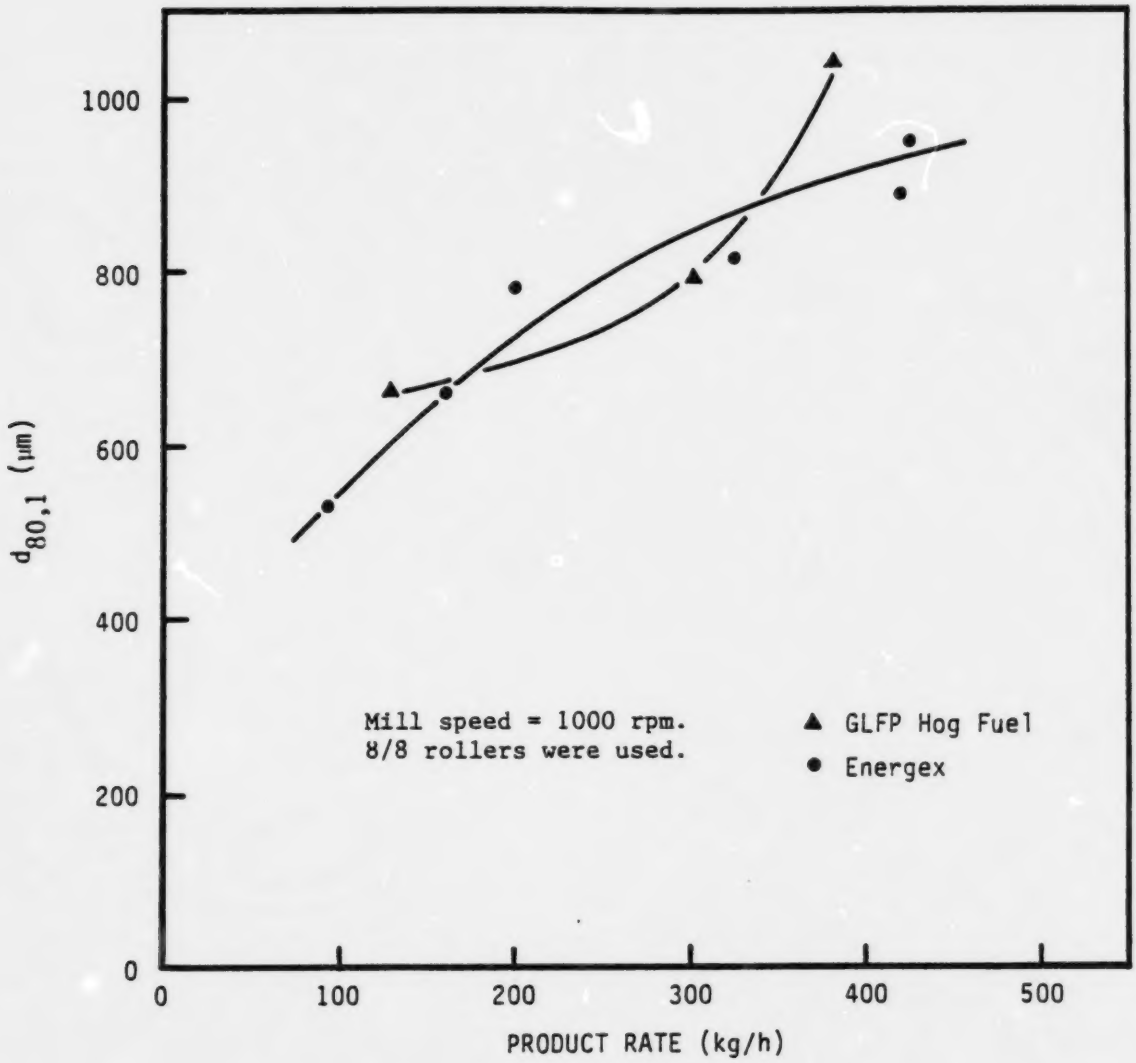


Fig. 4.16 1st Pass Product 80%-passing Size vs Product Rate for GLFP Hog Fuel and 'Energex'

finer sizes than 8/16 rollers. This is because Energex is relatively easy to grind and the 8/8 rollers have more grinding surface per unit of roller length.

In Figure 4.16, first pass product size is plotted against product rate for 8/8 rollers and a rotational speed of 1000 rpm. Not surprisingly, the data indicate that product size increases as the product rate is increased. The trend that is shown will continue until the maximum product rate, above which the mill becomes blocked or the motor is overloaded, is reached.

4.2.3 Particle Characteristics of Ground Energex

Energex is composed of sawdust and bark. Sawdust is a fibrous material, consisting of wood fibre bundles. What is commonly known as bark is in fact the outer bark of a tree, which is dead material. It consists of short, weak cells. The inner bark, which is living, may be stringy and difficult to comminute (3). Bark from log debarking operations consists of outer and inner bark, and a proportion of wood. Thus the bark component of Energex is comprised of fibrous and non-fibrous material.

Both fibrous and non-fibrous particles are evident in ground Energex products. Particle shapes and characteristics may be seen in Figures 4.13 and 4.14. The fibrous particles are larger and lighter in colour. They are somewhat similar to the broken fibre bundles that are found in ground wood chips. The non-fibrous particles are dark brown and powdery.

In the above-mentioned Figures, the largest size fractions, +3350 µm and 2000 to 3350 µm, consist of large, flattened fibre bundles which are often partially split in the direction of the fibres. The aspect ratio of these particles ranges from about 1 to 2. Similar fibre bundles predominate in the

1168 to 2000, 850 to 1168, and 425 to 850 μm size fractions. The smaller size fraction, -212 μm, is a dark powder which contains very many fine, non-fibrous particles.

4.2.4 Power Consumption for Energex Grinding

Power consumption data for Energex grinding with 8/8 rollers and 8/16 rollers are presented in Table A.5. The total power consumption for 8/8 rollers at 1000 rpm is plotted against product rate in Figure 4.17 for Energex and GLFP hog fuel. The power consumption increases fairly rapidly with product rate, and very rapidly with mill rotational speed, as shown in Figure 4.18 for product rates of the order of 300 to 400 kg/h.

A comparison of the power consumption for Energex grinding to that for grinding GLFP hog fuel shows that Energex requires less power than hog fuel. No data have been found in the literature for the energy requirements of comminution of wood wastes to fine particle sizes with other types of equipment, but it is likely that, if the Szego Mill requires less energy to grind wood chips than other mills, it also requires less energy to grind wood wastes.

4.2.5 Energex Grinding with the Commercial-Size (46-cm) Mill

A number of tests were made with Energex using the 46-cm mill. The primary objectives were to compare the performance of the commercial-size mill with that of the pilot-size mill, and to obtain information for designing an industrial wood-grinding unit.

The rotational speed of the 46-cm mill in GCI's laboratory is not easily varied, unlike the speed of the 22-cm mills. A set mill speed of 600 rpm was

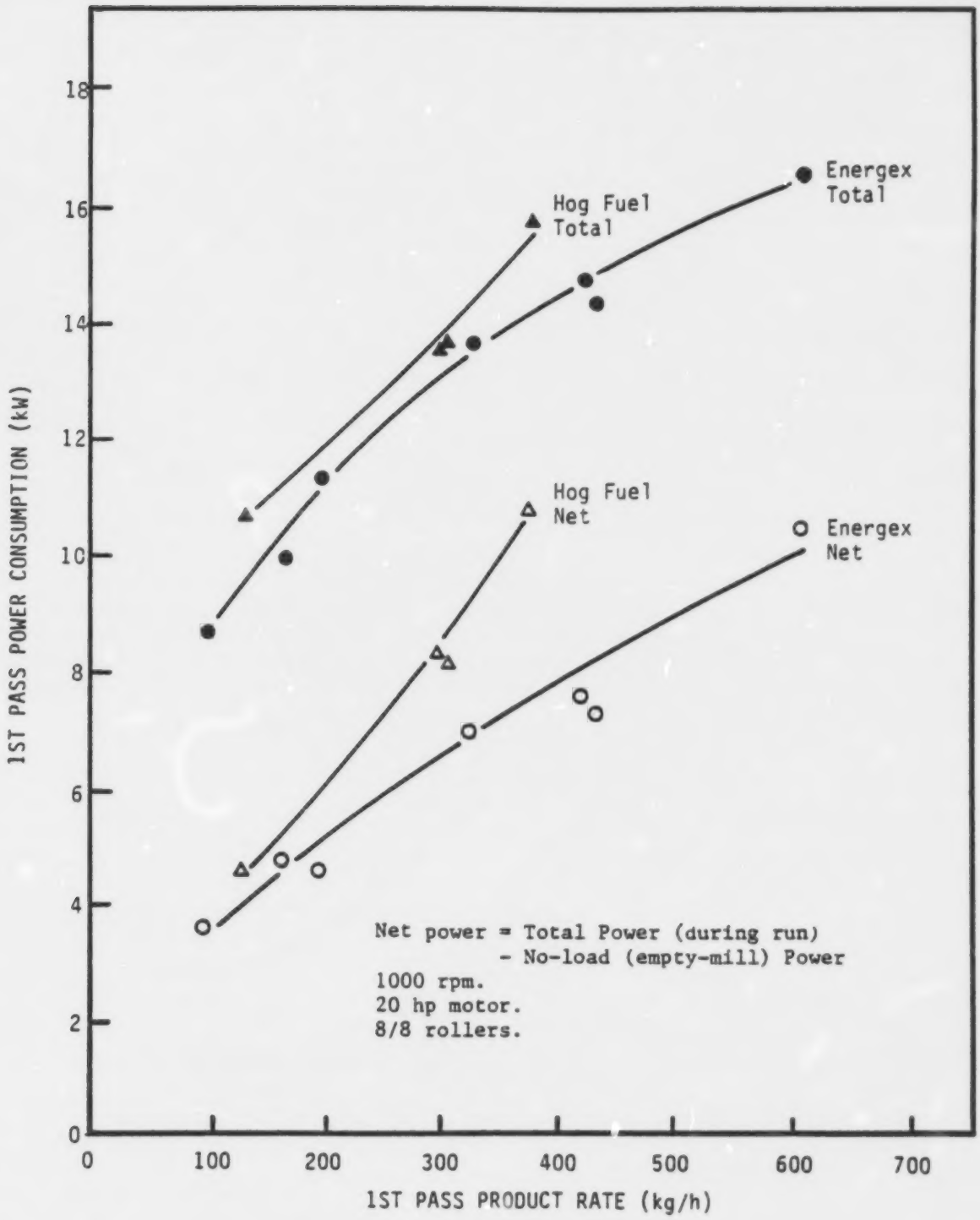


Fig. 4.17 Power Consumption vs Product Rate for GLFP Hog Fuel and 'Energex'

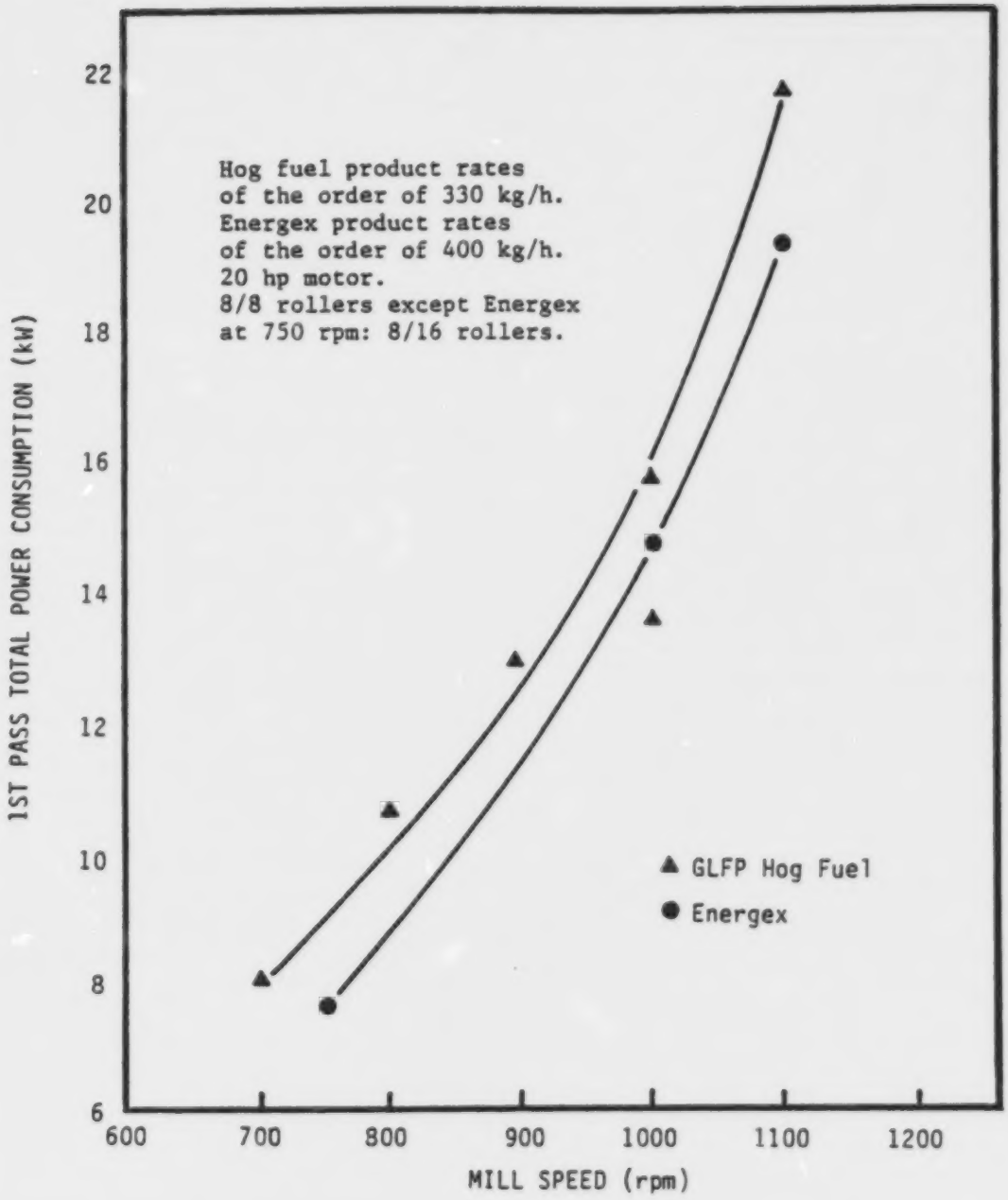


Fig. 4.18 Total Power Consumption vs Mill Speed for GLFP Hog Fuel and 'Energex'

used. This speed is estimated to be approximately equivalent to a speed of 1200 rpm in the pilot-size mill in that the product sizes of the two mills are similar.

Runs were made with product rates up to about 2000 kg/h. For each run, one pass through the mill was made. A large degree of size reduction was achieved in one pass. It would have been very laborious to make additional passes, hence multi-pass grinding studies were restricted to the pilot-size mill.

The 46-cm mill is equipped with rollers with 6-mm square ridges and grooves.

The results of the runs are summarized in Table A.6. The data indicate that all the products are well within the size specification. A particle-size distribution for one of the runs, Run 75, is shown in Figure 4.19. For comparison, the size distribution of the first pass product of Run 52 (22-cm mill) is plotted in the same figure. The two size distributions are very similar. The product rate for Run 75 was 3.6 times that for the first pass of Run 52.

Product size is plotted against product rate in Figure 4.20. The curve is similar to that for the 22-cm mill (see Figure 4.16) except that it appears to level off at about 800 μm. Runs at higher rates to confirm this behaviour were not possible because both the product collection system and the mill driver were at maximum capacity.

Particle characteristics other than size are essentially the same as those of the 22-cm mill products.

The average power consumption for 'Energex' grinding with the 46-cm mill is shown in Figure 4.21. The tests were approximately 3 minutes long, and, for

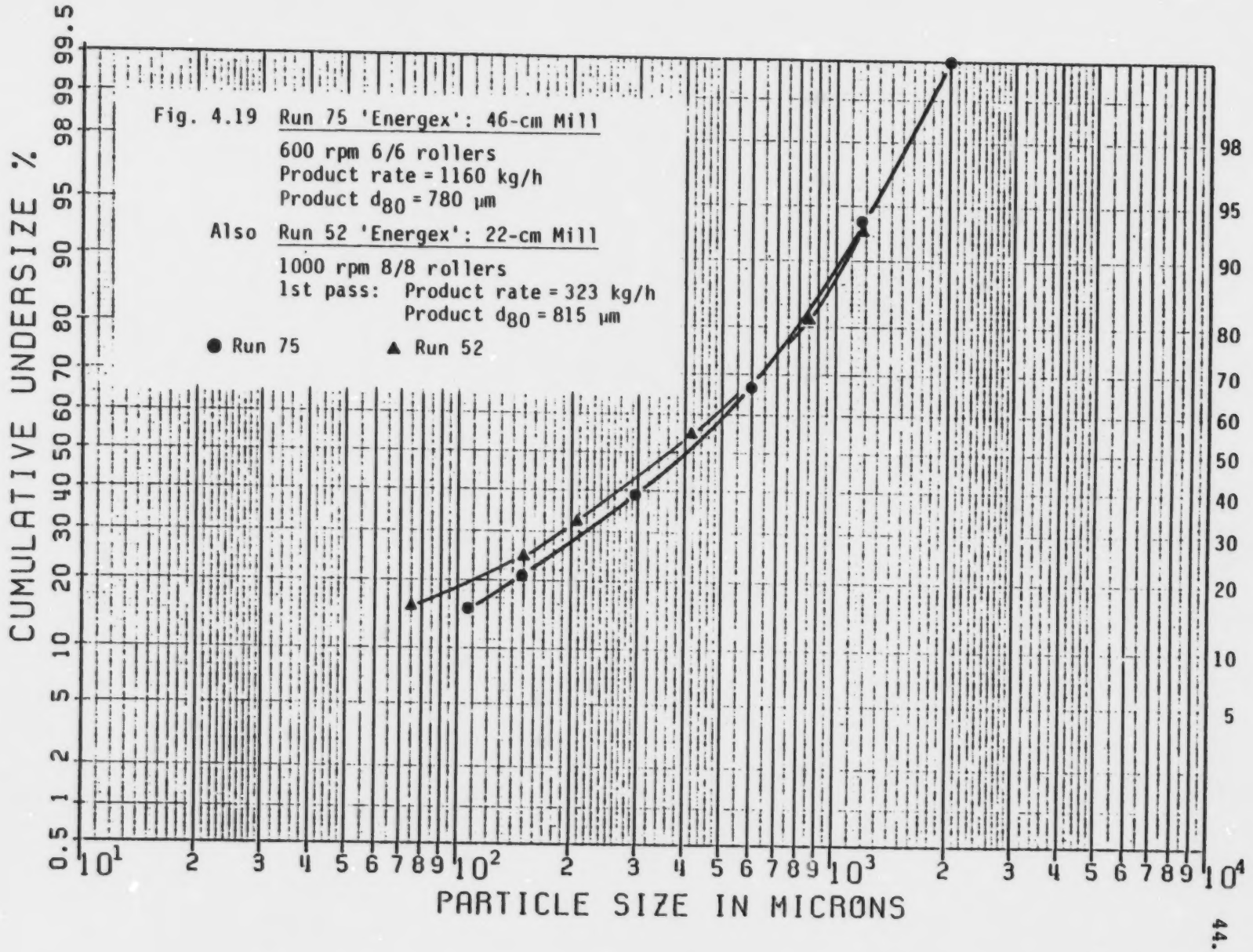


Fig. 4.19 Run 75 'Energex': 46-cm Mill
600 rpm 6/6 rollers
Product rate = 1160 kg/h
Product d_{80} = 780 μm
Also Run 52 'Energex': 22-cm Mill
1000 rpm 8/8 rollers
1st pass: Product rate = 323 kg/h
Product d_{80} = 815 μm
● Run 75
▲ Run 52
CUMULATIVE UNDERSIZE %
0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.5
98 95 90 80 70 60 50 40 30 20 10 5
10^1 2 3 4 5 6 7 8 9 10^2 2 3 4 5 6 7 8 9 10^3 2 3 4 5 6 7 8 9 10^4
PARTICLE SIZE IN MICRONS

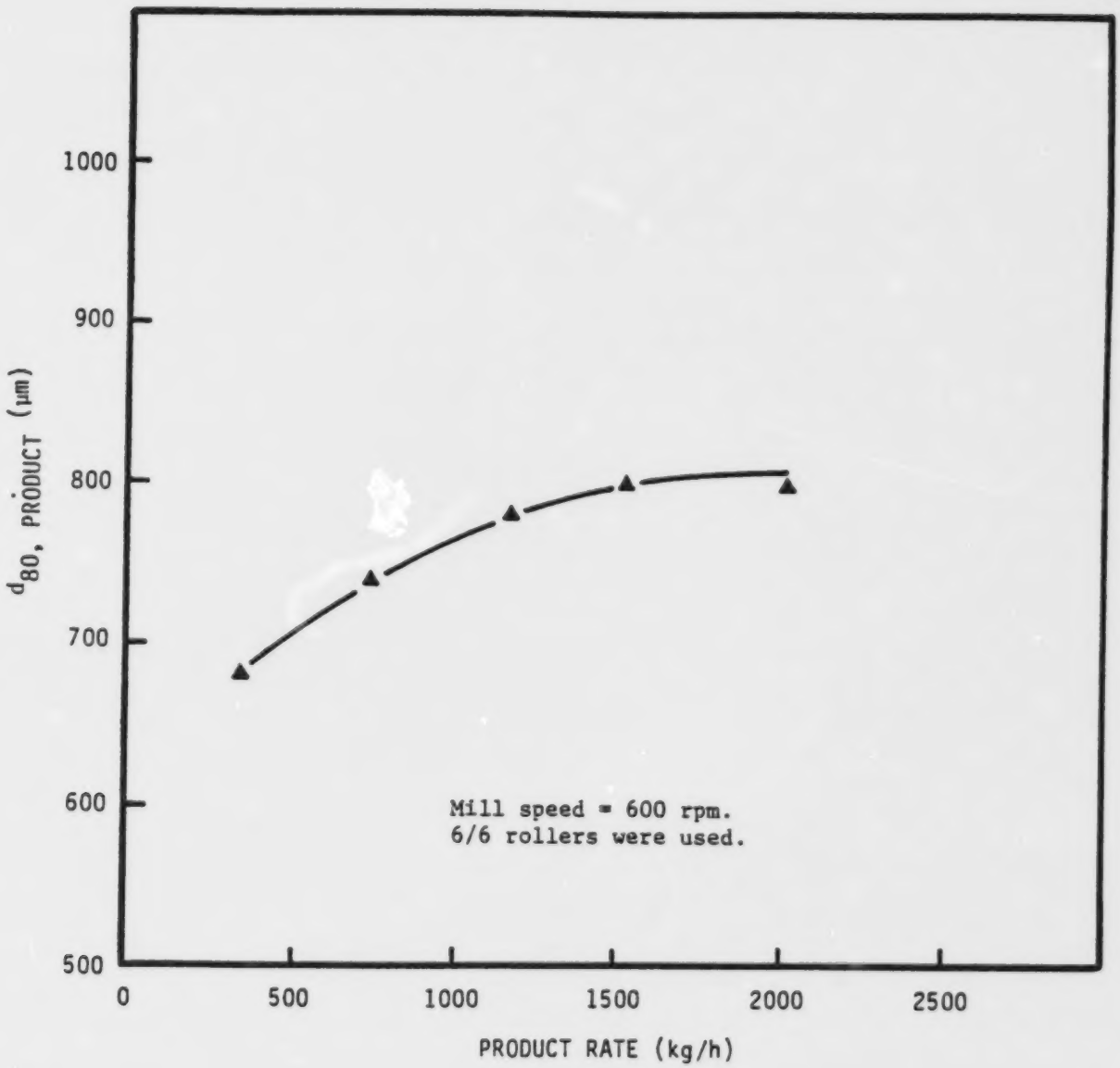


Fig. 4.20 Product 80%-passing Size vs Product Rate for 'Energex' Grinding with 46-cm Mill

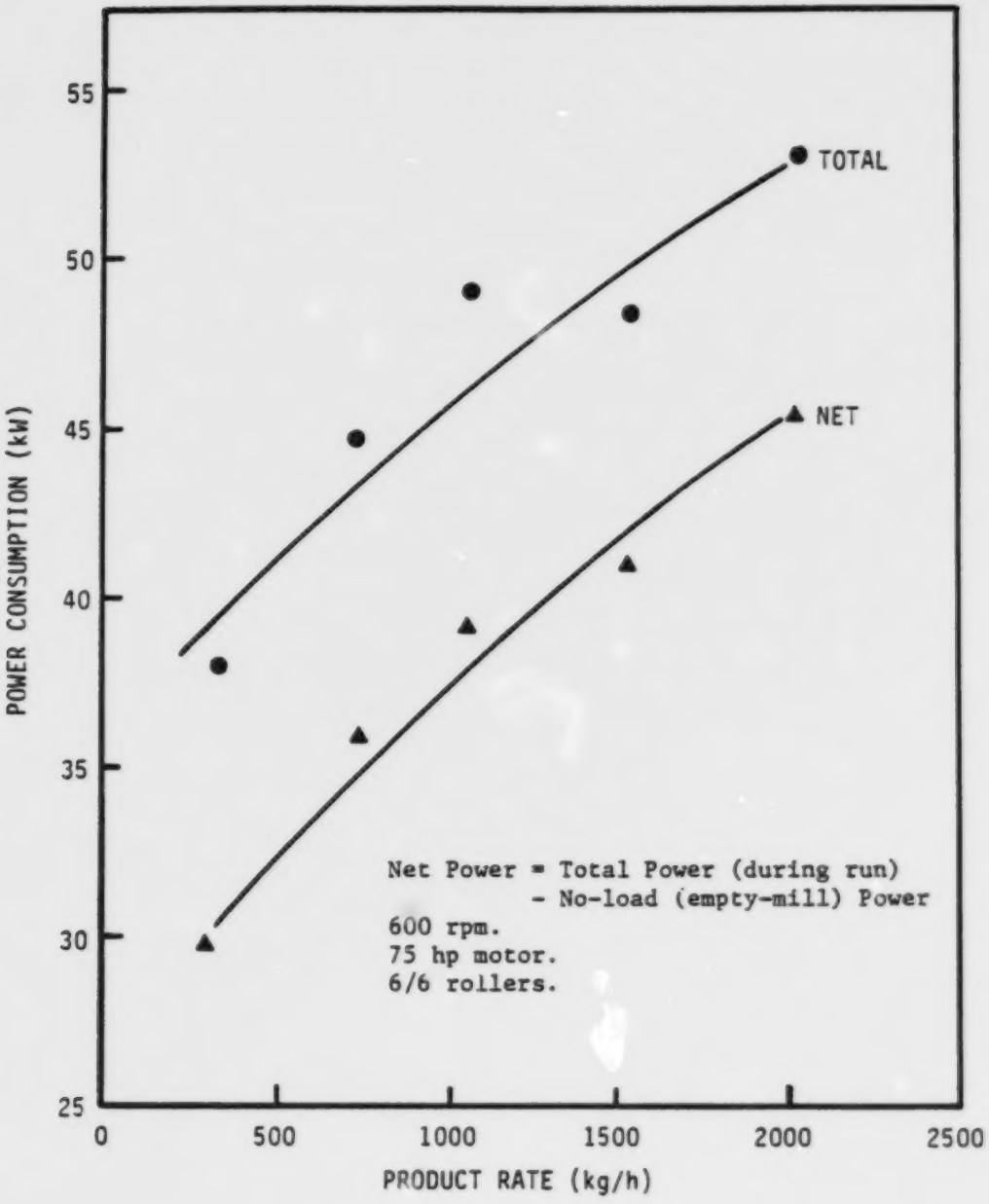


Fig. 4.21 Power Consumption for 'Energex' Grinding with the 46-cm Mill

product rates of 1160 kg/h and higher, the power consumption was increasing at the end of the test. It was not possible to carry out tests much longer than 3 minutes with 'Energex' at rates above 1000 kg/h because the capacity of the existing product collection system would have been exceeded. In tests done by GCI with the 46-cm mill with other materials, steady state was reached after longer periods of operation.

The total specific energy consumption for Run 75 was 45 kWh/tonne ODW, which is, within the limits of experimental error, the same value as that for Run 52 (22-cm mill; similar particle-size distribution). Specific energy consumption decreases as the product rate is increased, e.g., the value for Run 77 is 28 kWh/tonne ODW. The product rate for Run 77 was 2010 kg/h, compared to 1160 kg/h for Run 75. The product size for Run 77 was somewhat larger than that for Run 75, but both products were well within the size specification. The conclusion is that the mill should be run at a maximum rate in order to use energy most efficiently.

4.2.6 GLFP Hog Fuel Grinding

This material consists mostly of bark and partly of wood, originating from several species, from the debarkers at a Great Lakes Forest Products' pulp mill in northern Ontario. A sample of this material is shown in Figure 4.11b. The hog fuel, when received, is moist (of the order of 50% total moisture) and contains many large pieces, some greater than 20 cm in length. The high moisture content makes it difficult, if not impossible, to pulverize without adding water (wet grinding) or drying the material. Since a dry mill product is desirable, the hog fuel was air-dried to a moisture content of about 10%.

The maximum size of particles in the feed to the 22-cm Szego Mill is of the order of 2 cm in width so the following procedure was used: After drying, the hog fuel was screened with a 1-cm screen. The oversized material was broken up with a small hammer mill, which has an outlet screen with 1.5-cm openings. The hammer mill product was then mixed with the material that passed through the 1-cm screen. This procedure simulated hogging of the wood residue to a nominal size of about 1 cm. A sample of mixture and the fractions which comprise it is shown in Figure 4.23.

In the experiments with GLFP hog fuel, mill rotational speeds ranging from 700 to 1100 rpm were used. Runs were made with feed rates up to about 750 kg/h. To study the grinding characteristics of the material, at least two passes were made in each test. Only 8/8 rollers were used. The 8/16 rollers would perform less well than the 8/8 rollers, as in 'Energex' grinding. Additional tests were made in which the moisture content was varied and frozen hog fuel was ground. These are described in Section 4.2.10.

Data from runs with GLFP hog fuel at various operating conditions are presented in Table A.7. The set of results for a typical run (Run 60) is shown in Table 4.1. From the table it may be seen that hog fuel grinding is more difficult than 'Energex' grinding, but less difficult than moist aspen grinding. Under similar operating conditions, hog fuel mill product is coarser than 'Energex' product, and hog fuel grinding consumes more energy.

The feed and product particle-size distributions of Run 60 are shown in Figure 4.22. Samples of Run 60 feed and products and their respective size fractions are shown in Figures 4.23, 4.24, and 4.25.

The product size specification is met, e.g., in one pass through the pilot-size Szego Mill with 8/8 rollers, at a mill speed of 1000 rpm, with a

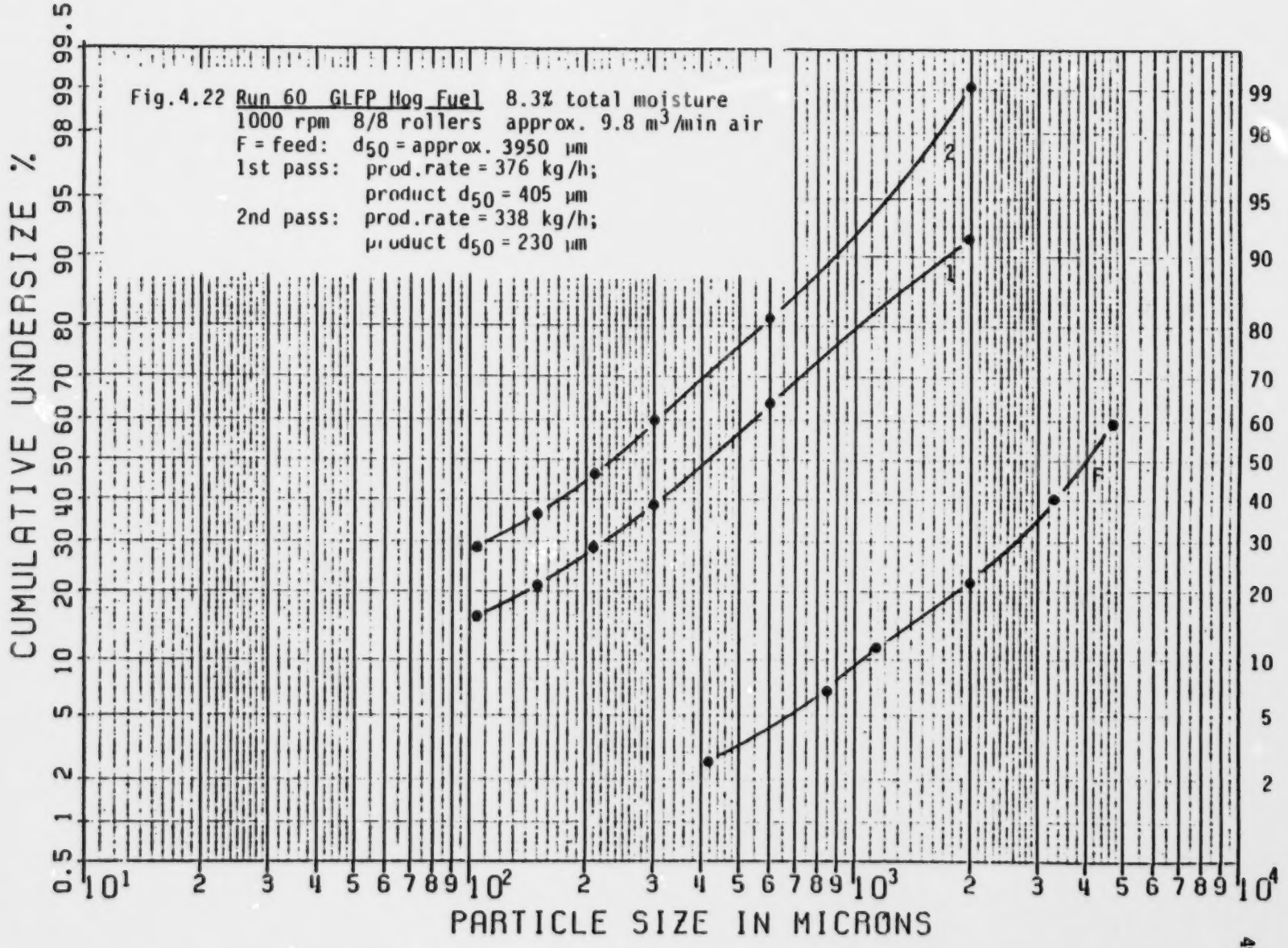


Fig.4.22 Run 60 GLFP Hog Fuel 8.3% total moisture
1000 rpm 8/8 rollers approx. 9.8 m³/min air
F = feed: d50 = approx. 3950 µm
1st pass: prod.rate = 376 kg/h;
product d50 = 405 µm
2nd pass: prod.rate = 338 kg/h;
product d50 = 230 µm
CUMULATIVE UNDERSIZE %
PARTICLE SIZE IN MICRONS
0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.5
10¹ 2 3 4 5 6 7 8 9 10² 2 3 4 5 6 7 8 9 10³ 2 3 4 5 6 7 8 9 10⁴
99 98 95 90 80 70 60 50 40 30 20 10 5 2
2
1
F

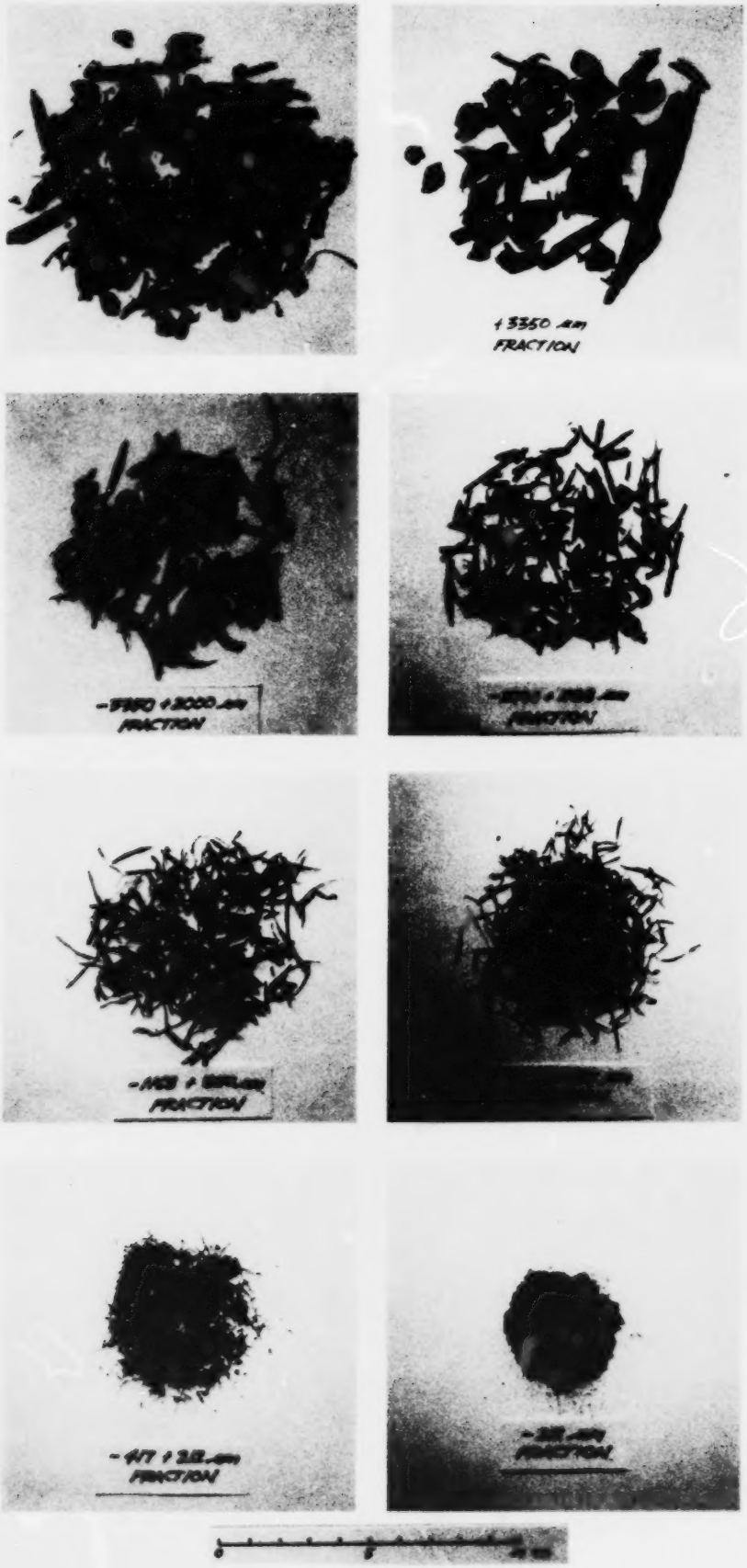
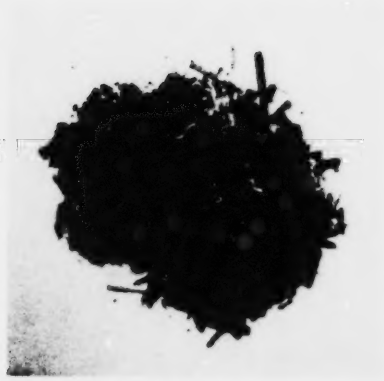


Fig. 4.23 GLFP Hog Fuel Run 60 feed and feed size fractions
Note: Percentages indicate relative amounts.

Total



1.9 wt%

6.0 wt%

10.8 wt%

8.0 wt%

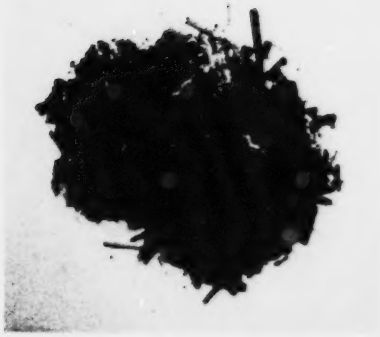
21.5 wt%

22.3 wt%

29.5 wt%

Fig. 4.24 GLFP Hog Fuel Run 60 1st pass product and its size fractions
Note: Percentages indicate relative amounts.

Total



0.1 wt%

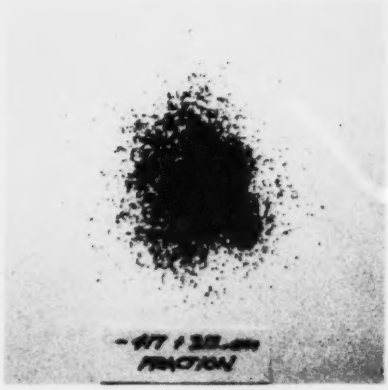
0.7 wt%

3.9 wt%

4.9 wt%

17.4 wt%

22.3 wt%



50.7 wt%

Fig. 4.25 GLFP Hog Fuel Run 60 2nd pass product and its size fractions
Note: Percentages indicate relative amounts.

product rate of 365 kg/h. The data of Table 4.2 indicate the relationship between the maximum product feed rate to the pilot mill at which the size specification is met, and the mill rotational speed.

The decrease in product particle size with mill rotational speed is shown in Figure 4.15. The increase in product size as the product rate is increased at constant rotational speed is shown in Figure 4.16. In both of the figures, the relationships for hog fuel may be compared to those for 'Energex'.

The differences in curvature for Energex and hog fuel are due to the different natures of these materials. Energex consists of many small particles compressed into 6-mm diameter pellets. The pellets are readily crushed, releasing small particles. The curves for Energex tend to be flat because the production of fine particles is relatively insensitive to mill operating conditions.

Hog fuel, on the other hand, contains a significant proportion of large particles, some of the order of 1 cm wide and 8 cm long. When the mill is operated at low rotational speed or high product rate, the coarse particles are not broken efficiently. This is reflected in a large product particle size.

4.2.7 Particle Characteristics of Ground GLFP Hog Fuel

Hog fuel consists primarily of residue from a debarking operation and, therefore, it is composed mostly of the outer bark of the tree. Like 'Energex', it contains both fibrous and non-fibrous material, although the proportion of fibrous material is higher.

The hog fuel fed to the mill consists of several different types of particles in a broad range of sizes (see Figure 4.23). Large chunks of bark and wood appear in the +3350, 2000 to 3350, and 1168 to 2000 µm fractions; stringy fibrous particles predominate in the 850 to 1168, and 417 to 850 µm fractions; and non-fibrous particles comprise most of the 212 to 417, and -212 µm fractions. The fibrous particles are light-coloured, while the non-fibrous particles are reddish-brown.

The particle shapes and characteristics of Szego-milled hog fuel can be seen in Figures 4.24 and 4.25. Milling flattens, breaks up and cuts fibrous particles, and crushes non-fibrous particles. The overall effect is that the aspect ratio of the particles decreases, and thus the particles become more uniform in shape, as they are reduced in size. This may be observed by comparing, say, the 1168 to 2000 µm fraction of the feed, first-pass and second-pass products in Figures 4.23 to 4.25. Nevertheless, fibrous particles are more prevalent in the larger size fractions, and non-fibrous particles in the smaller size fractions.

When hog fuel is ground at moisture contents in excess of about 15 wt% (total basis), agglomerates are formed in large numbers. Most of the particles larger than 1168 µm are agglomerates. They have the appearance of reddish-brown pancakes. Many of these agglomerates consist of relatively large fibrous particles encased in a mass of fine non-fibrous particles.

4.2.8 Power Consumption for GLFP Hog Fuel Grinding

Power consumption data for hog fuel grinding at various operating conditions are listed in Table A.7. The dependence of total and net power on product rate, and total power on mill speed are shown in Figures 4.17 and 4.18,

respectively. Again, direct comparisons to 'Energex' grinding may be made, and it is evident that grinding hog fuel is a more difficult task than grinding 'Energex'.

4.2.9 GLFP Hog Fuel Grinding with the 46-cm Mill

Two runs were made with GLFP hog fuel in the 46-cm mill. The same rollers and mill speed were used as for the runs with Energex using the commercial-size mill (see Section 4.2.5).

The results of the runs are presented in Table A.8. The maximum product rate was about 500 kg/h. There was a large degree of size reduction in one pass. The products were well within the 1000-μm size specification.

The results of Run 71 (46-cm mill; Table A.8) may be compared with those of Run 66 (22-cm mill; Table A.7). The product sizes of the two runs are very similar. The product rate of Run 71 is approximately 40% higher than that of Run 66. The total specific energy consumption of Run 71 is 107 kWh/tonne ODW, about 50% higher than that of Run 66.

These results were not as good as expected. It was predicted that the product rate of hog fuel with the 46-cm mill would be 3 or more times the rate with the 22-cm mill, as was the case with Energex.

It appears that modification of the 46-cm mill will be required in order to run hog fuel at rates of the order of 1000 kg/h and higher. Many pieces of hog fuel feed are 8 cm long or longer. These do not readily pass down the narrow vertical spaces between the rollers of the 46-cm mill. They do tend to get caught between the rollers, and especially between the two scrapers, installed to prevent excessive buildup of material on the wall, and the rollers adjacent to these scrapers. Such problems were not encountered with the 22-cm

mill, which has larger spaces between its 3 rollers, and is not equipped with scrapers.

4.2.10 Influence of Feed Moisture Content and Temperature on GLFP Hog Fuel Grinding

One of the objectives of this study was to investigate the grinding of frozen bark. It was envisioned that wood waste might be more brittle and therefore easier to grind when frozen than when at room temperature. It seemed likely that the advantage of grinding frozen material would depend on its moisture content. Another objective of this study was to determine the effects of moisture content on grinding, so the two objectives were combined in a series of tests with hog fuel (which is mostly bark) feeds, at room and cryogenic temperatures, over a range of moisture contents.

In these tests, small (approximately 0.5 kg) batches of hog fuel were hand-fed to the mill. The product collection system was not used. Instead, mill product was simply allowed to fall into a collection drum. These tests lasted about one minute, so feed rates (but, because of accumulation in the mill, not necessarily product rates) were of the order of 30 kg/h. Such rates are an order of magnitude lower than the usual pilot unit rates, so the results differ quantitatively from pilot-scale results, but qualitatively, the results and trends are the same. For example, if there is an advantage to grinding frozen hog fuel with a particular moisture content at 30 kg/h, there will be a similar advantage for grinding that material at 300 or 3000 kg/h.

The reason that small batches of material were run was that liquid nitrogen (boiling point -196°C) was used to freeze the material for the "cryogenic" tests. Approximately 1L of liquid nitrogen was mixed into a batch

of hog fuel before grinding. This was sufficient to freeze the material and to keep it frozen by evaporation of excess nitrogen while the material was fed to the mill. The mass ratio of liquid nitrogen to oven-dry wood was of the order of 1.3. Corresponding tests were carried out with hog fuel at room temperature.

Product particle size is plotted against moisture content for cryogenic and room-temperature feed in Figure 4.26. It can be seen that there is little advantage to grinding frozen hog fuel, and it is, in fact, disadvantageous at high moisture contents. The reason that there is so little advantage is that most of the energy input to this and any other grinding mill is converted to thermal energy, heating the material and the mill surroundings (21). The intense crushing and shearing forces within the mill rapidly counteract the cooling effect of the liquid nitrogen. In fact, the "cryogenic" products were only of the order of 10°C cooler than the non-cryogenic products, and all products were near ambient temperature.

The product size for frozen feed was somewhat smaller than that for room-temperature feed when the moisture content was below 20 wt%. This advantage appears to be due to better comminution of fibrous particles, which must have taken place near the top of the mill, while the particles were still frozen and brittle. The difference between grinding cryogenic and room-temperature feed decreases as the moisture content decreases. At a feed moisture content of about 20%, the product from cryogenic feed was considerably coarser than that from room-temperature feed. The former product also contained more moisture than the latter, so it seems that the presence of liquid nitrogen reduced the evaporation of moisture in the mill, keeping the

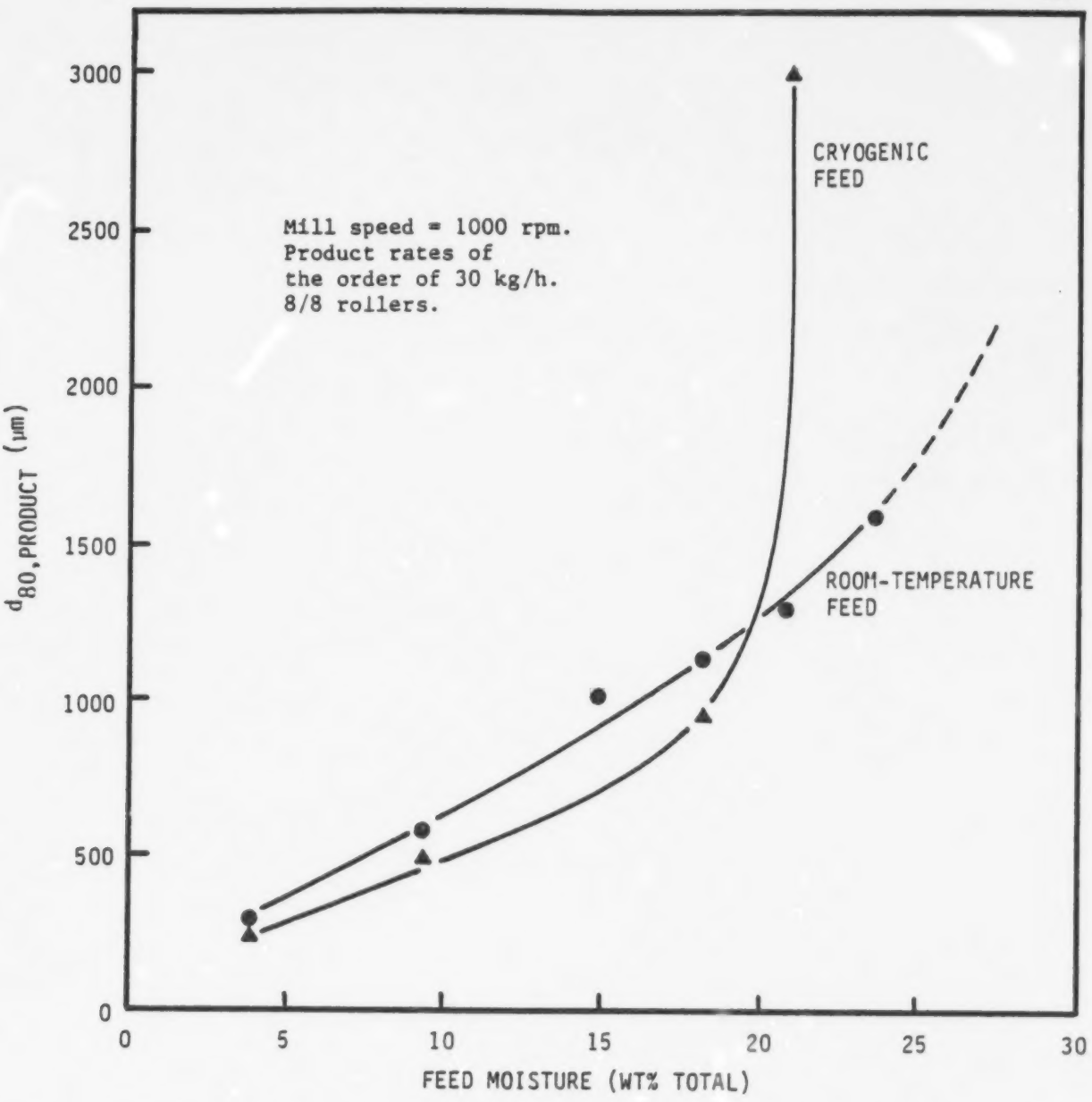


Fig. 4.26 GLFP Hog Fuel Product Size vs Feed Moisture

moisture content of the material above the level where grinding performance deteriorates dramatically.

In one or two experiments where less than excess liquid nitrogen was added to the feed, e.g., approximately 0.8 kg/kg ODW at 15% moisture, the product size was virtually identical to that of product from room-temperature feed at the same moisture content. This proves that there would be no advantage to milling frozen hog fuel at the coldest winter temperature. There would likely be some advantage in the grinding of fibrous particles if the mill were flooded with liquid nitrogen (special mill construction would be required) but this would be very uneconomical for a low-value product such as ground wood waste.

The moisture content of the feed has a major effect on grinding performance at any temperature, as long as moisture is present in larger than trace amounts, because the physical properties of wood vary significantly with moisture content (23, 19). In the tests with hog fuel at cryogenic and room temperatures, the feed moisture content was varied from 4 to 24%. Batches of hog fuel with various moisture contents were prepared by mixing measured amounts of water into air-dry material and allowing several days for the moisture to become evenly distributed, or by reducing the moisture content in a dryer.

For dry grinding (no water added during grinding), the mill performance decreases as moisture content increases: both the product size and the mill power consumption increase. From Figure 4.26 it can be seen that the product size fails to meet the 1000-μm specification when the moisture content of feed at room temperature exceeds 15%. At this and higher moisture contents, there are many agglomerates in the product (see Section 4.2.7).

When feed moisture content is in the range of 20 to 25%, there is a dramatic deterioration in performance. The amount of material retained in the mill (the hold-up) becomes large, and the product rate becomes small. The product is coarse and consists mainly of agglomerates. The rollers in the mill encounter increased resistance, so the power consumption increases. Clearly, the mill cannot be operated in this fashion continuously.

Imanudin (20) had some success in grinding moist hog fuel by employing a device which operated the feeder intermittently, allowing the mill to clear itself periodically of accumulated moist material. However, in an industrial setting, it would seem more practical to avoid the problems of grinding moist hog fuel by drying the material first, especially since wood waste must be fairly dry, preferably containing no more than 15% moisture, in order to be burned in suspension (14). Because the burner fuel must be dry, it would also be impractical to use wet grinding for hog fuel in an industrial setting.

4.2.11 Masson Bark Grinding

Several tests were carried out on the revamped (April 1985) pilot unit with black spruce bark from James Maclaren Industries' Masson, Quebec newsprint mill. This material is residue from the wet debarking operation near the Masson mill. It somewhat resembles hog fuel in appearance.

The bark was very wet when received (approximately two-thirds total moisture) and contained many large pieces, some up to about 0.5 m long. The wet bark was forced through the same hammer mill that was used to reduce large pieces of hog fuel, and, because the mill outlet has a screen with 1.5 cm diameter holes, loose "pellets" were formed. These were dried and Szego-milled.

Data from the test results with the revamped unit are listed in Table A.9. With the 22-cm mill operating at 1000 rpm, the maximum product rate of this material at which the size specification is met is about 500 kg/h (see Table 4.2). In general, Masson bark is more grindable, i.e., it is ground to finer sizes and requires less energy to grind, than GLFP hog fuel, and less grindable than Energex.

4.2.12 Closed-Circuit Grinding of Wood Waste

Closed-circuit grinding has been used in numerous applications to improve grinding efficiency by removing fines as they are generated in the mill. Feed material is ground and the product is passed through a classifier either by air sweeping or gravity feeding. The fines stream becomes the final product, and the oversize material is returned to the mill for further grinding, where it is mixed with fresh feed. In addition to increased efficiency, the advantages of closed-circuit grinding include well-controlled top size and higher mill throughput than for open-circuit grinding.

Figure 4.12 can be used to illustrate the advantages of closed-circuit grinding/classification in wood grinding. First, it should be noted that the products represented by the size distributions in Figure 4.12 are finer than specified for suspension burning (80% passing 1000 μm), and need no classification. For the sake of argument, however, it can be assumed that the desired cut size is 80% passing 500 μm. In one pass through the mill, at 323 kg/h, 63% of the mill product would be finer than 500 μm. A rate of 0.63 x 323 kg/h x 1/0.8 = 254 kg/h of classified product, would be achieved. A set point of 800 μm on the classifier would satisfy the above criteria. 21% of the

classifier feed would be oversize and would be reground in the mill after being mixed with 254 kg/h of fresh feed.

If multipass grinding were used, after three passes the product would conform to the specification of 80% -500 μm, but the production capacity would be reduced to 108 kg/h. As mill power remains constant during a run, the specific power consumption would theoretically be 2.35 times lower for closed-circuit operation. In reality, classification would require some power, and the advantage of closed-circuit grinding over multipass open-circuit grinding would be reduced to roughly 1.5 to 2 times.

In addition, classification "sharpness" varies with the material texture, size distribution, moisture content and density, and the classifier cut size. Typically, between 5 and 40% of the fines will end up in the oversize fraction, returning to the mill. This makes the system less efficient than ideal classification. The fines stream, however, is well sized, resulting in good top-size control.

In systems containing binary mixtures which exhibit different grindabilities, like hog fuel, which consists of wood and bark, the oversize stream from the classifier would contain mainly wood. It might be necessary to feed this stream to a stoker firing system or to grind it in a secondary mill. Returning this stream to the primary mill might increase the wood fraction in the mill, decreasing the mill production rate. The system would eventually arrive at equilibrium. These problems would have to be solved in the plant, when an industrial demonstration unit is installed.

Wood classifiers are rather bulky items, available only in large sizes. In the laboratory, some mill products were screened with a 76-cm vibrating screen. In contrast to air classification, screening provides almost ideal

separation of the incoming stream into oversize and undersize fractions. By a very laborious procedure involving repeated grinding, screening of mill product and mixing of the oversize material with fresh feed, it might be possible to approximate closed-circuit grinding in the laboratory. However, proper investigation of closed-circuit wood grinding should be done with an air classifier on an industrial scale. This should be explored when a demonstration unit is built.

5.0 DEVELOPMENT OF THE SZEGO MILL FOR INDUSTRIAL WOOD GRINDING

Tests with the 22-cm and 46-cm mills in the laboratory have demonstrated the feasibility of grinding wood chips and wood wastes to fine sizes. They have also shown how the design of the general-purpose mills should be modified for wood grinding.

The next step is to proceed from laboratory units to industrial demonstration units. The advantages of the Szego Mill should be proven on an industrial scale in a continuous wood-grinding application. In addition, it would be impractical to conduct long tests at high rates, to investigate the benefits of closed-circuit grinding, or to integrate the mill with wood handling equipment, in the laboratory. Such work must be done in an industrial setting.

The first industrial units will likely be for grinding hog fuel, bark or other wood residue to sizes suitable for suspension burning. A 32-cm mill, which incorporated a number of improvements, was recently designed and has been installed at several locations. A mill of this type would be suitable for grinding hog fuel at a rate of about 0.5 tonne/h, and could be assembled within

several months. The design of a 64-cm mill for wood grinding is planned. This mill would grind hog fuel at a rate of about 2 tonne/h.

6.0 CONCLUSIONS

General

1. The technical feasibility of grinding moist ("green") wood chips, pelletized wood waste, hog fuel and bark to fine particle sizes has been demonstrated. Most of the tests were done with the pilot-size (22-cm diameter) mill. Sufficient performance data were obtained with the pilot unit for initial optimization. Additional data were obtained with the commercial-size (46-cm diameter) mill for the design of an industrial unit.

2. Product particle size decreases with mill rotational speed and increases with product rate. The mill power consumption increases with mill rotational speed and with product rate. Quantitative relationships between the above variables were established for grinding moist aspen chips, 'Energex' pelletized wood waste and GLFP hog fuel with the 22-cm mill.

3. In order of increasing difficulty of grinding, the materials tested were: 'Energex' pelletized wood waste; black spruce bark from Masson, Quebec; hog fuel from northern Ontario; moist spruce chips; and moist aspen chips. Grinding moist wood chips is considerably more difficult than grinding dry wood wastes.

4. Fibrous particles, which are characteristic of wood, are tougher than non-fibrous particles, which are characteristic of bark. It appears that fibrous particles are broken by flattening, splitting and cutting actions in the mill, while non-fibrous particles are broken by crushing.

Wood Chip Grinding

1. A typical set of results for moist aspen chip grinding with the 22-cm mill is as follows: A product with 92 wt% passing 2000 μm (measured by dry sieving) is obtained in two passes, at 1100 rpm, at a rate of 170 kg/h (85 kg ODW/h), using 8/16 rollers. The energy consumption is approximately 340 kWh/tonne ODW.

2. Agglomerate formation from fine particles limits the degree of size reduction of moist wood chips. There is little, if any, size reduction after the second pass through the mill. This phenomenon is strongly dependent on the moisture content. No agglomerates were formed in as many as seven passes with air-dry aspen chips.

3. The 8/16 rollers are superior to the 8/8 rollers for grinding moist wood chips because the 16-mm-wide grooves do not become clogged with moist wood pulp. The 8/8 rollers are superior to the 8/16 rollers for grinding dry wood chips (and dry wood wastes) because there is more grinding surface per unit of roller length, resulting in a finer product size.

4. The specific energy consumption of moist wood chip comminution with the Szego Mill is of the order of 400 kWh/tonne ODW, which is considerably lower than the value of 1810 kWh/tonne ODW cited for an industrial disk refiner (22). A direct comparison of the degrees of size reduction is not possible at this time because different methods of size analysis were used in each case.

5. The product particle size of moist aspen is considerably finer than that of air-dry aspen after one pass through the 22-cm mill. After two passes, the particle sizes of moist and dry products are similar. After more than two passes, the air-dry product is finer than the moist product, which, because of

agglomeration, does not become any finer. For similar product rates of oven-dry wood, the specific cumulative energy consumption (kWh/tonne ODW) was similar for moist and air-dry aspen grinding after two passes.

Wood Waste Grinding

1. 'Energex' pelletized wood waste is readily ground to meet the size specification for suspension burning (80 wt% passing 1000 μm). One set of conditions for the 22-cm mill which meets the specification is as follows: one pass through the mill, at 800 rpm, at a rate of 400 kg/h, using 8/8 rollers. At these conditions, the specific energy consumption is 23 kWh/tonne ODW.

2. The capacity of the 46-cm mill for grinding 'Energex' is three to four times that of the 22-cm mill. The specific energy consumption of the large mill is similar to that of the smaller mill. Long duration tests are required to confirm the steady state power consumption of the 46-cm mill at rates exceeding 1000 kg/h.

3. Great Lakes Forest Products (GLFP) hog fuel is more difficult to grind than 'Energex'. One set of conditions for the 22-cm mill which meets the size specification for suspension burning is as follows: one pass through the mill, at 1000 rpm, at a rate of 365 kg/h, using 8/8 rollers. At these conditions, the specific energy consumption is 46 kWh/tonne ODW.

4. Modification of the 46-cm mill is required in order to increase its hog fuel grinding capacity, which should be three or four times that of the 22-cm mill.

5. Grinding performance decreases as the moisture content of hog fuel increases. At feed moisture contents above 15 wt% (total basis), many agglomerates are formed. A dramatic decrease in performance occurs when the

feed moisture content is 20 to 25%. Since dry product is required for suspension burning, wood waste should be at least air-dry before comminution.

6. There is little difference between the results of grinding hog fuel fed at cryogenic temperature and at room temperature. Cryogenic grinding of wood waste would be very uneconomical.

7.0 RECOMMENDATIONS

Industrial Development

1. The Szego Mill should be tested in a continuous, industrial, wood-grinding operation. A 32-cm mill, suitable for grinding about 0.5 tonne/h of hog fuel, is available. A 64-cm mill, with about four times the capacity of the 32-cm mill, is planned.

2. Additional tests should be done with the 46-cm mill in GCI's laboratory with the particular materials to be ground at the industrial facilities. Appropriate modifications should be made. If hog fuel is to be ground, modifications must be made to accomodate long particles. If moist wood chips are to be ground, rollers with wide grooves must be installed.

Laboratory Tests

1. A few additional, selected tests should be made with the 22-cm mill to confirm the relationships established for that mill, e.g., a test should be done with moist aspen chips at a product rate of 1100 rpm and a mill speed of 1100 rpm (see Figure 4.6).

2. A more precise feeder, recently acquired by GCI, should be used for additional test work.

3. Particle size analysis of moist wood chip products by dry sieving with the 'Ro-Tap' sieve shaker, and by wet sieving with the 'Bauer-McNett' fibre classifier, should be compared. The particle size distributions of Szego Mill products determined by the former method could then be compared to the size distribution of other comminution products determined by the latter method.

4. The dimensions of particles in the different size fractions of typical products should be measured by microscopic techniques.

5. Power consumption should be measured with a kilowatt meter to confirm the accuracy of the method employed for these tests.

6. A pilot-scale test should be made with GLFP hog fuel of approximately 15% moisture, the moisture content at which small-scale test product no longer meets the size specification for suspension burning. Correlations should be made between the small-scale tests to investigate the effects of moisture content, and pilot-scale tests.

7. Wet grinding of wood chips for chemical conversion applications should be studied. It is likely that finer particle sizes could be achieved by wet grinding than by dry grinding.

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APPENDIX A

TABULATED DATA FOR WOOD CHIP AND WOOD WASTE GRINDING TESTS

Table A.1

Results of Aspen Chip Grinding with 8/16 Rollers

Run	Mill Speed	1st Pass		1st Pass Product Size		2nd Pass	2nd Pass Product Size	
		Avg. Product Rate	Moisture	d_{50}	d_{80}	Avg. Product Rate	d_{50}	d_{80}
	(rpm)	(kg/h)	(wt% total)	(μm)	(μm)	(kg/h)	(μm)	(μm)
40	1200	268	45.0	1380	3700	159	910	1390
41	1200	181	45.0	1110	3000	187	880	1430
39	1200	148	47.4	950	1540	-	-	-
36	1100	188	45.6	1020	2220	190	930	1580
35	1100	120	45.8	1030	2100	217	910	1480
37	1100	108	45.2	1020	1910	124	930	1450
33	1000	189	50.2	1540	3470	190	1340	2680
32	1000	162	47.2	1780	3750	223	970	1950
38	1000	86	43.5	1290	2570	149	970	1660
34	900	163	49.4	2550	6500	167	1290	3080

Note: Runs are listed in order of decreasing mill speed and product rate.

Table A.2

Power Consumption for Aspen Chip Grinding with 8/16 Rollers

		1st Pass			2nd Pass		
Run	Mill Speed (rpm)	Avg. Prod. Rate (kg/h)	Total Power (kW)	Net Power (kW)	Avg. Prod. Rate (kg/h)	Total Power (kW)	Net Power (kW)
40	1200	268	19.2	12.6	159	16.8	10.6
41	1200	181	16.8	9.0	187	17.6	11.2
39	1200	148	16.2	10.1	-	-	-
36	1100	188	15.0	8.9	190	14.6	8.2
35	1100	120	13.9	7.3	217	15.6	9.2
37	1100	108	13.6	8.2	124	14.9	8.3
33	1000	189	12.7	6.5	190	13.2	7.1
32	1000	162	13.3	7.3	223	13.3	7.3
38	1000	86	10.6	5.0	149	11.8	6.8
34	900	163	10.7	5.8	167	11.2	5.2

Notes: Net Power = Total Power (during run) - No-load (empty mill) power.
All runs with 30 hp motor.

Table A.3

Comparison of Moist and Air-dried Aspen Chip Grinding

Run	Pass	Moisture (wt% total)	Avg. Prod. Rate (kg/h)	Product Size d_{50} (μm)	Total Power Consumption (kW)
Moist Chips					
31	1	50.8	206	2500	17.0
31	2	46.1	219	1150	17.0
17	1	46.0	200	2540	17.5
17	2	--	200	1060	16.8
17	3	--	200	950	15.7
16	1	44.1(F:49.7)	125	1540	16.0
16	2	39.1	125	1050	14.0
16	3	33.7	125	1060	16.1
Dry Chips					
26	1	--(F:13.5)	220	6900	14.7
26	2	--	190	2900	11.2
26	3	--	200	1440	11.3
26	4	--	280	790	11.4
26	5	--	240	640	11.2
26	6	--	240	380	11.3
26	7	--	280	305	11.4
24	1	11.4(F:13.5)	81	4050	12.3
24	2	9.8	97	1190	10.1
24	3	--	127	690	10.3
24	4	--	95	385	9.2
24	5	--	97	323	8.5

Notes: All runs with 8/8 rollers, at 1000 rpm.
Product rates for Runs 16 and 17 are approximate.
F = Feed.

Table A.4

Comparison of Moist and Oven-dried Spruce Chip Grinding

Moist Chips

Run	Pass	Moisture (wt% total)	Avg. Prod. Rate (kg/h)	Product Size d_{50} (μm)	Total Power Consumption (kW)
22	1	26.5(F:42.1)	120	1690	10.3
22	2	21.8	120	1420	10.0
22	3	19(est'd)	200	1420	10.2
		Dry Chips			
23	1	2.3(F:2.8)	140	1680	8.9
23	2	2.4	160	870	7.8
23	3	2.4(est'd)	140	430	7.5
23	4	2.4(est'd)	170	225	7.6

Notes: Both runs were made with 8/8 rollers, at 900 rpm.
F = Feed.

Table A.5

Results of 'Energex' Grinding with 8/8 Rollers

Run	Mill Speed (rpm)	1st Pass Avg. Product Rate (kg/h)	1st Pass Product Size d_{50} (µm)	1st Pass Product Size d_{80} (µm)	1st Pass Power Consumption Total (kW)	1st Pass Power Consumption Net (kW)
58	1100	435	350	860	19.3	11.2
56	1000	426	440	950	14.2	7.2
57	1000	419	415	890	14.7	7.5
52	1000	323	355	815	13.6	6.9
53	1000	198	340	780	11.3	4.5
69	1000	160	290	665	9.9	4.9
68	1000	93	250	530	8.6	3.6
9	750	626	500	1000	11.3	5.4
		Results for 'Energex' Grinding with 8/16 Rollers				
45	1200	875	385	890	27.0	18.8
46	1200	648	295	760	23.1	15.4
47	1200	409	280	660	21.1	13.2
49	1000	703	520	1030	17.0	8.8
48	1000	536	555	1040	15.0	8.7
43	1000	482	440	920	14.8	8.4
42	1000	338	480	930	13.5	7.5
44	750	477	880	1470	15.3	10.3
50	750	344	590	1070	7.6	2.3
51	750	198	510	795	6.6	2.4

Notes: Runs are listed in order of decreasing mill speed and product rate.
'Energex' feed size = 6 mm = 6000 µm (monosize).
Feed moisture content = approx. 7 wt% (total).

Table A.6

Results of 'Energex' Grinding with the 46-cm Mill

Run	Avg. Product Rate (kg/h)	Product Size d_{50} (μm)	Product Size d_{80} (μm)	Avg. Power Consumption Total (kW)	Avg. Power Consumption Net (kW)
77	2010	390	800	53.0	45.4
76	1520	405	800	48.3	41.0
75	1160	395	780	48.9	39.1
74	722	363	740	44.7	35.7
73	340	305	680	38.0	29.7

Notes: Runs are listed in order of decreasing product rate.
Mill speed was 600 rpm.
6/6 rollers were used.

Table A.7

Results of GLFP Hog Fuel Grinding

Run	Mill Speed (rpm)	1st Pass Avg. Product Rate (kg/h)	Feed Moisture (wt% total)	Feed Size d_{50} (μm)	Feed Size d_{80} (μm)	1st Pass Product Size d_{50} (μm)	1st Pass Product Size d_{80} (μm)	1st Pass Power Consumption Total(kW)	1st Pass Power Consumption Net(kW)
66	1100	343	10.8	2750	5300	340	850	21.8	16.4
60	1000	376	8.3	3950	5600	405	1040	15.7	10.7
61	1000	301	9.6	3600	7100	520	1170	13.5	8.1
67	1000	300	10.8	2300	4500	350	795	13.4	8.2
62	1000	128	9.6	2850	5500	305	665	10.6	4.5
63	900	316	9.6	3750	7700	460	1120	12.9	8.4
64	800	283	9.6	2940	5900	510	1210	10.6	4.6
12	750	750	6.5	1600	3500	700	1400	14.8	8.7
11	750	500	6.5	3000	6000	700	1650	12.2	6.1
10	750	500	6.5	1600	3500	580	1300	12.1	6.1
65	700	378	10.8	3200	5800	830	1820	8.0	3.1

Notes: Runs are listed in order of decreasing mill speed and feed rate.
All runs with 8/8 rollers.
Product rates for Runs 10, 11, & 12 are approximate.
Net Power = Total power (during run) - No-load (empty mill) power.

Table A.8

Results of GLFP Hog Fuel Grinding with the 46-cm Mill

Run	Feed Moisture (wt% total)	Feed Size d_{50} (μm)	Feed Size d_{80} (μm)	Avg. Product Rate (kg/h)	Product Size d_{50} (μm)	Product Size d_{80} (μm)	Power Consumption Total (kW)	Power Consumption Net (kW)
71	11.2	2680	5700	484	360	870	46.9	38.6
72	11.3	3550	6800	255	254	660	42.5	33.0

Notes: Mill speed was 600 rpm.
6/6 rollers were used.

Table A.9

Results of Masson Bark Grinding

Run	Mill Speed (rpm)	1st Pass Product Rate (kg/h)	Feed Moisture (wt% total)	Feed Size d_{50} (μm)	Feed Size d_{80} (μm)	1st Pass Product Size d_{50} (μm)	1st Pass Product Size d_{80} (μm)	1st Pass Power Consumption Total(kW)	1st Pass Power Consumption Net(kW)
14	1000	500	10	3000	7000	465	1000	21.3	15.1
13	750	500	6	7800	14000	730	1600	11.9	6.2
15	600	500	7	7400	12000	750	1400	7.8	1.8

Notes: These results are for tests with the revamped (April 1985) product collection system.
8/8 rollers were used.
Product rates are approximate.
Net Power = Total Power (during run) - No-load (empty mill) Power.

APPENDIX B

PERFORMANCE TESTING FOR WET GRINDING OF BARLEY AND CRACKED GRAIN CORN IN THE SZEGO MILL

INTRODUCTION

In this appendix, the results of the study on wet grinding of barley and corn with the Szego mill, will be presented and discussed. The purpose of this study was to evaluate the performance of the Szego mill for grinding these materials and prepare the grains as feedstocks to a fermentation process.

EXPERIMENTAL

An SM-220-1 mill was used in all experiments. This mill was equipped with three, 30 cm long rollers (4 mm ridge/groove). The grains (see Table B.1 for the feed size distributions) were fed from a hopper by a screw conveyor feeder to the mill. Tap water was simultaneously fed through a rotameter at predetermined rates.

Several open-circuit, single-pass grinding experiments were performed at different operating conditions which are summarized in Table B.2. In addition, multi-pass grinding experiments were done at a selected operating condition (850 rpm, 450 kg/h of solids and 600 kg/h of water). The thick slurry produced in each pass was collected and fed to the mill for the next pass.

The particle size distribution of the product from each experiment was determined by wet sieving. 40-50 g samples of the product were taken and wet sieved with water for 15 minutes, followed by drying of the sieves, and then weighing the material left on the sieves.

RESULTS AND DISCUSSION

Open-Circuit, Single-Pass Grinding

The results obtained at different operating conditions are shown in Figures B.1-B.4. It is obvious from these data that even though increasing the

rotational speed of the mill gives a product with a finer median size, the product size distribution becomes broader, i.e. a large amount of coarse grains are still left unground in the product. This result is interesting because wet grinding of brittle materials such as coal does not exhibit this trend.

A few experiments in dry grinding of corn and barley were carried out at different rotational speeds, and it was found that the shape of the size distribution curve did not change with the rotational speed, unlike in wet grinding. The possible reasons for the above phenomena with respect to the rotational speed are the following; (i) the material properties of grains, which are more plastic and sticky, (ii) ineffective nipping of the particles by the smooth surface of the ridges on the rollers, at high speeds, and (iii) decrease in mean residence time when the speed is increased in the case of wet grinding.

The performance of the mill will be considerably better in larger units where the nipping of the particles by the rollers is much more effective due to the roller diameter. In addition, using rough ridges instead of smooth ridges on the rollers will decrease the slippage of particles at the grinding zone.

The effect of the feed rate is as expected for both, corn and barley; higher rates give a coarser product. The feed rate effect is more significant in the case of corn grinding, the lower feed rate (250 kg/h) products at different speeds have median sizes which are smaller by a factor of 1.5 than the corresponding sizes at the higher feed rate.

The specific energy consumption at 850 rpm and 450 kg/h of solids, for corn and barley were 14.8 and 9.5 kWh/ton, respectively.

Multi-Pass Grinding

The main objective of the multi-pass grinding experiments was to obtain a finer product, by providing a longer residence time for the material in the mill. The data from these experiments are shown in Figures B.5 and B.6. Only the size distributions of the products of the 1st, 3rd and 5th pass are given in order to avoid crowding of the size distribution curves. It can be observed that a very fine product (80% passing 50 μm) can be easily produced at a rate of 450 kg/h of solids, in just three passes.

Size (μm)	Cumulative Percent Undersize	
	Corn	Barley
4000	91.2	100.0
2362	39.0	4.4
1651	24.6	0.4
850	13.6	0.2
425	7.3	0.1

Table B.1: Size distributions of the barley and corn feeds used in the experiments

	Barley		Corn	
Solids feed rate, kg/h	450	650	250	450
Water feed rate, kg/h	600	840	360	540
Rotational speed, rpm	675 850 1000	675 850 1000	675 850 1000	675 850 1000

Table B.2: Summary of the open-circuit, single-pass grinding experiments

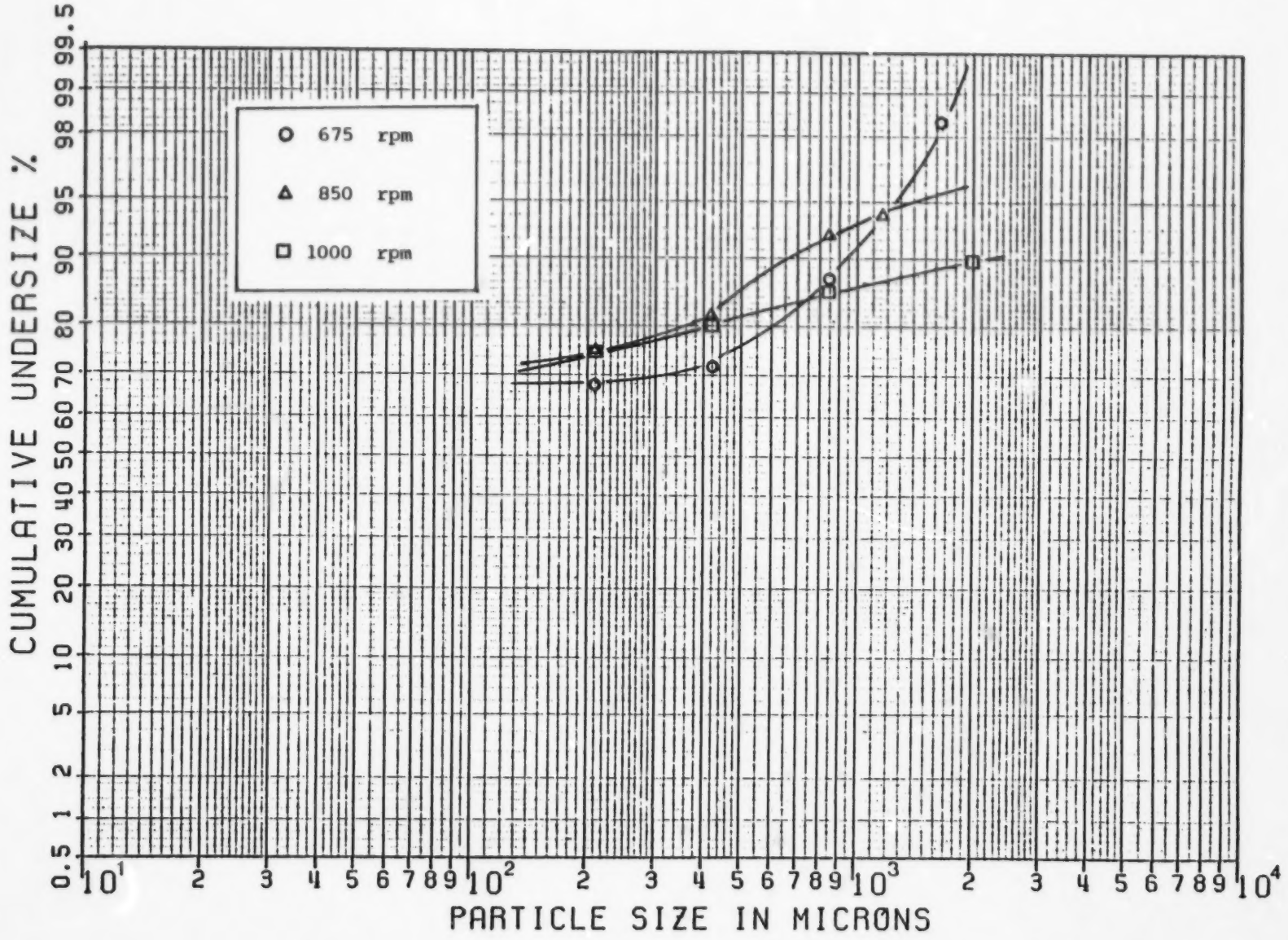

FIGURE B.1 PARTICLE SIZE DISTRIBUTIONS AT VARIOUS ROTATIONAL SPEEDS FOR WET GRINDING OF BARLEY IN THE SZEGO MILL. FEED RATES: 450 kgh^{-1} BARLEY, 600 Lh^{-1} WATER.

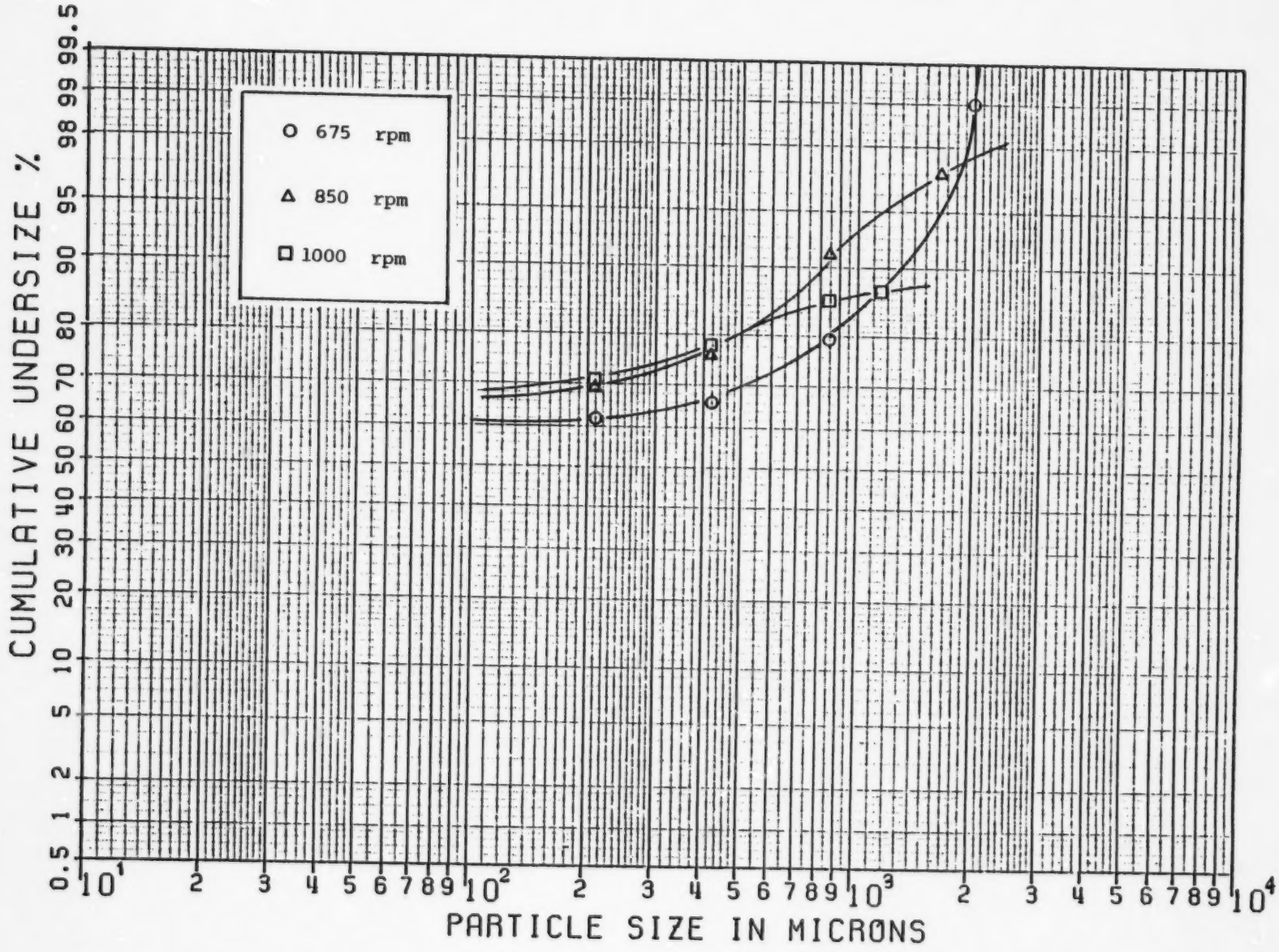

FIGURE B.2 PARTICLE SIZE DISTRIBUTIONS AT VARIOUS ROTATIONAL SPEEDS FOR WET GRINDING OF BARLEY IN THE SZEGO MILL. FEED RATES: 650 kgh^{-1} BARLEY, 840 Lh^{-1} WATER.

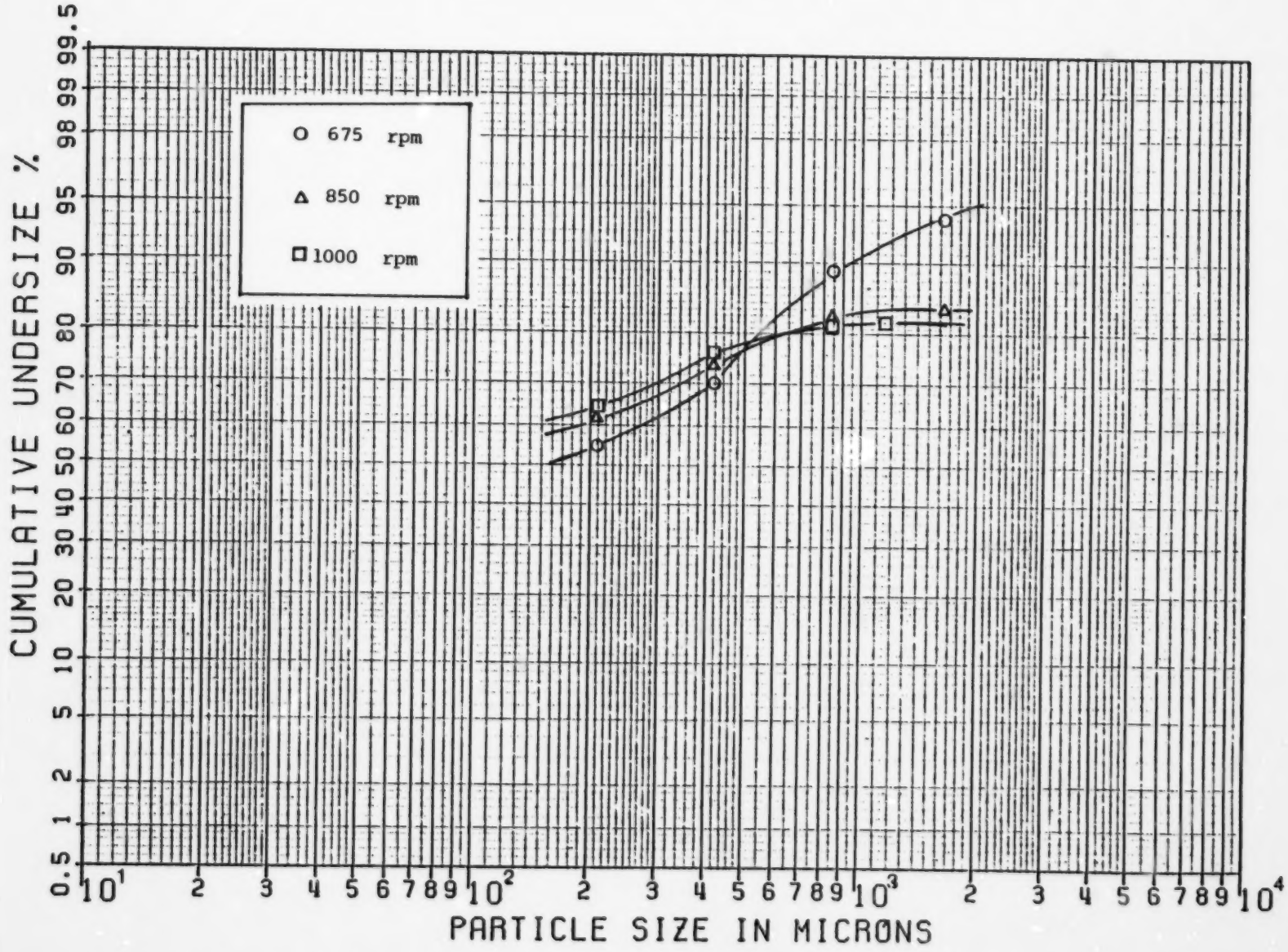

FIGURE B.3 PARTICLE SIZE DISTRIBUTIONS AT VARIOUS ROTATIONAL SPEEDS FOR WET GRINDING OF CRACKED GRAIN CORN IN THE SZEGO MILL. FEED RATES: 250 kgh^{-1} CORN, 360 Lh^{-1} WATER.

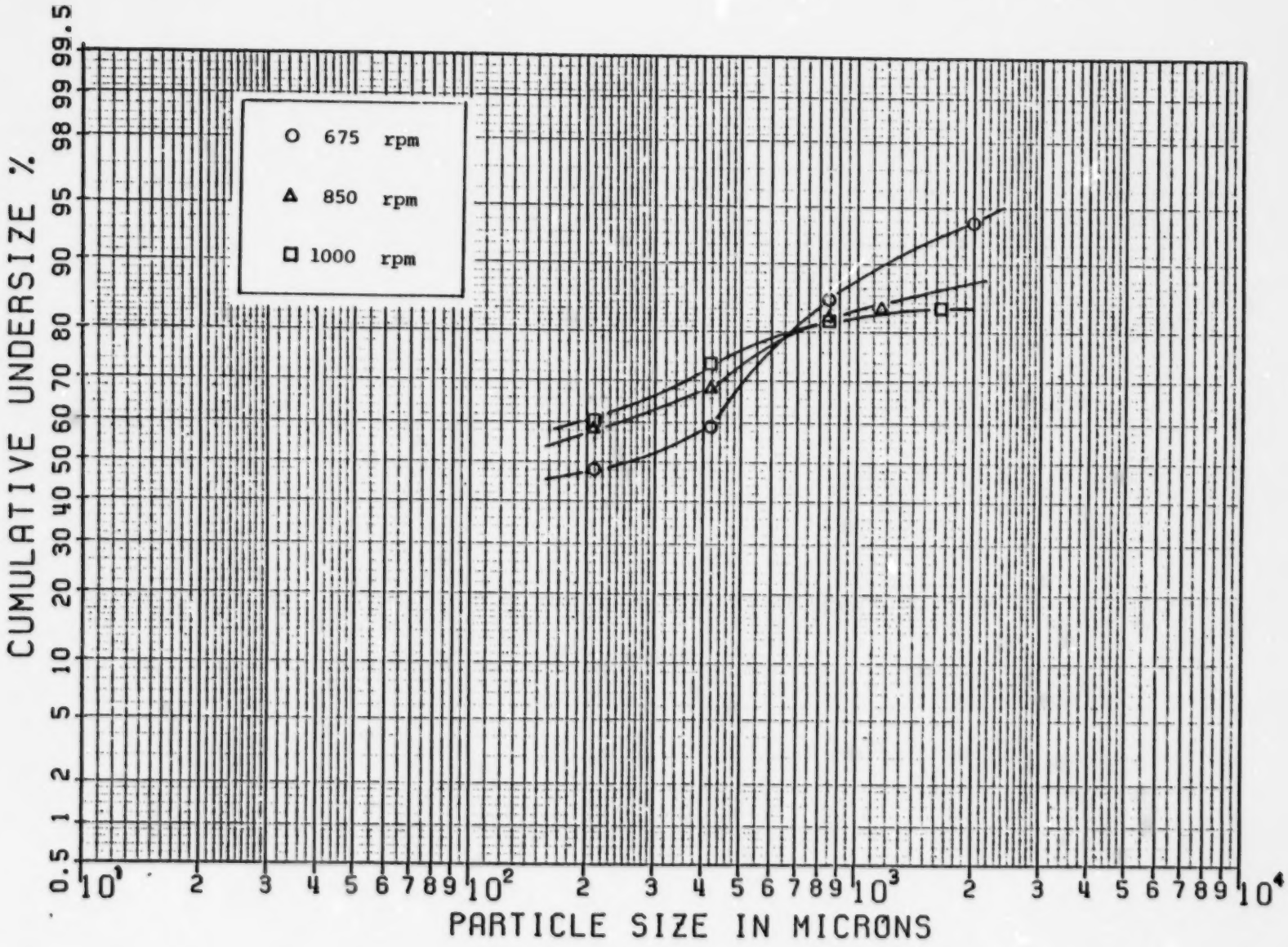

FIGURE B.4 PARTICLE SIZE DISTRIBUTIONS AT VARIOUS ROTATIONAL SPEEDS FOR THE WET GRINDING OF CRACKED GRAIN CORN IN THE SZEGO MILL. FEED RATES: 450 kgh^{-1} CORN, 570 Lh^{-1} WATER.

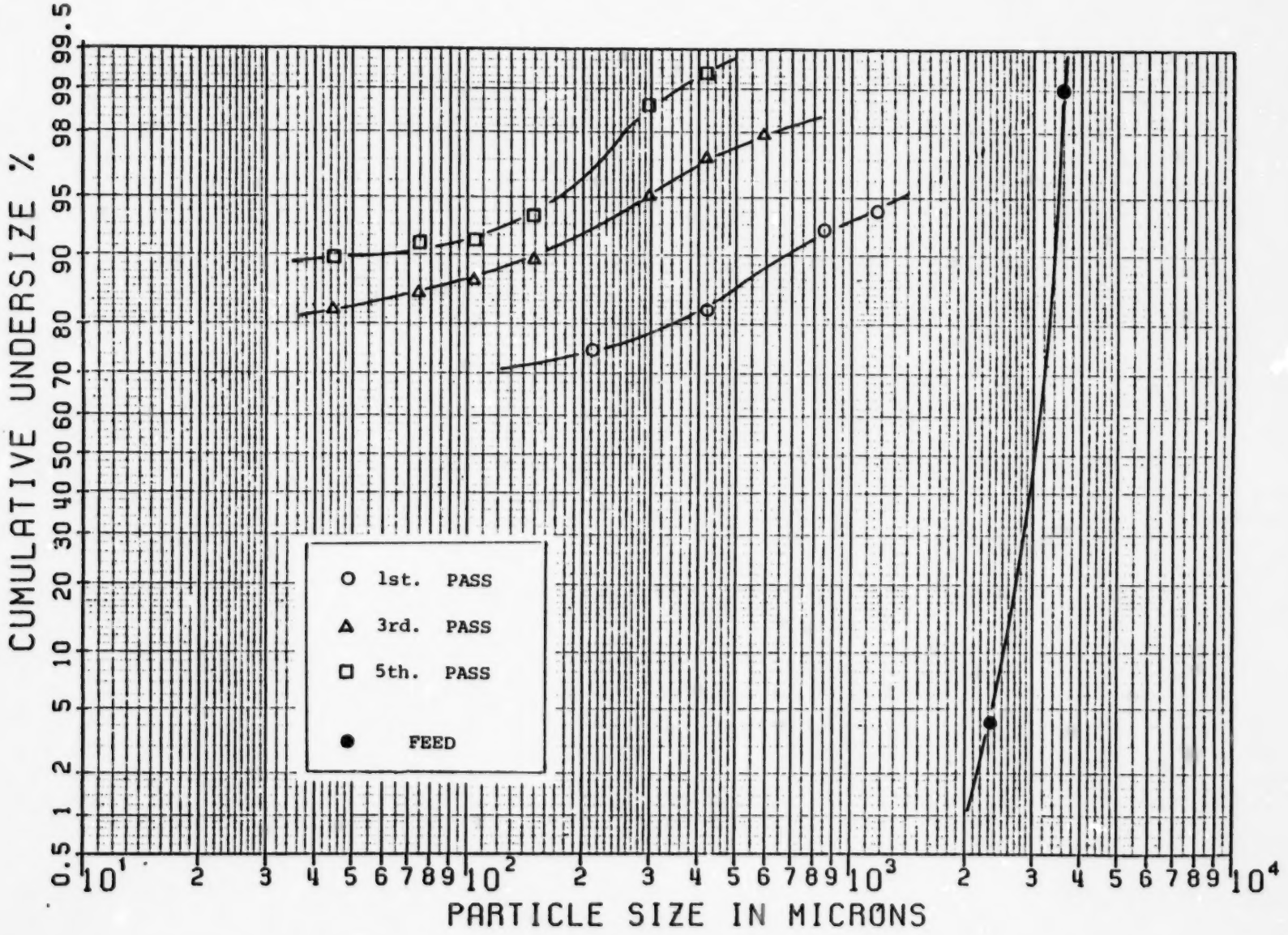

FIGURE B.5 PARTICLE SIZE DISTRIBUTIONS FOR THE MULTI-PASS, WET GRINDING OF BARLEY IN THE SZEGO MILL. FEED RATES: 450 kgh^{-1} BARLEY, 600 Lh^{-1} WATER.

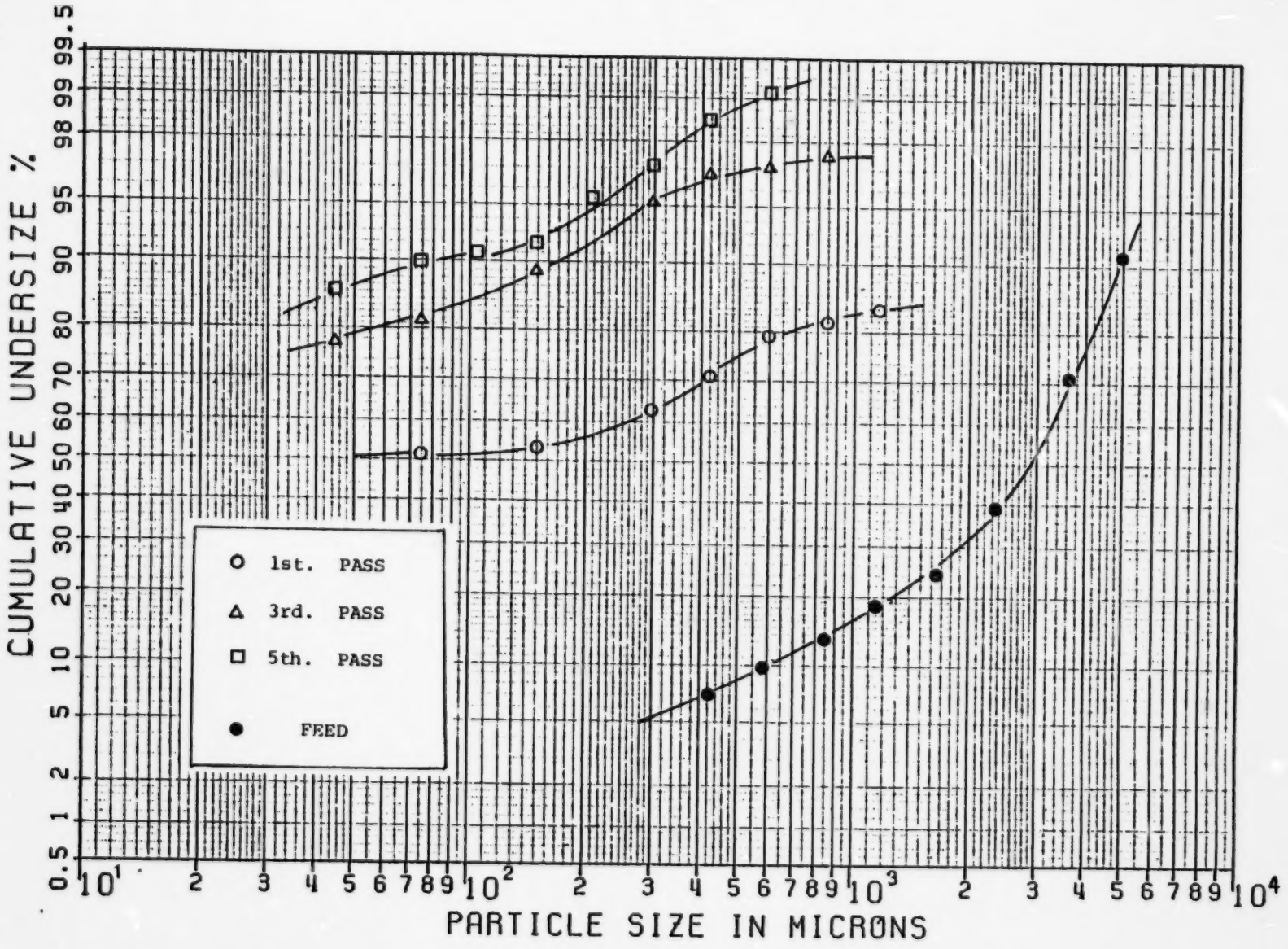

FIGURE B.6 PARTICLE SIZE DISTRIBUTIONS FOR THE MULTI-PASS, WET GRINDING OF CRACKED GRAIN CORN IN THE SZEGO MILL. FEED RATES: 450 kgh^{-1} CORN, 500 Lh^{-1} WATER.

FERMENTATION RESULTS

Initial hydrolysis/fermentation results clearly show the importance of grinding. The processing was done by Dr. S. Parekh, a member of Professor M. Wayman's reserach group in the Chemical Engineering Department at the University of Toronto. Experimental details are available. The summary results follow:

Corn

For single-pass ground material, the best results were 761 kg total sugars/tonne, an 88.6% yield, and 396 L ethanol/tonne, an overall yield of 73.4%.

The 5-pass material gave 779 kg/t (90.5%) and 416 L/t, respectively, for an overall yield of 77.1%.

Barley

Single-pass material: 737 kg/t (88.1%) and 359 L/t (68.4%).

5-pass material: 800 kg/t (95%) and 423 L/t (80.5%)

The alcohol produced at the St. Lawrence Reactors (POS project #84-701 progress report #2) was 373 L/t, with a considerably longer fermentation time.

It is possible to improve grinding further, both by changing conditions and going to additional passes. In view of the considerable differences exhibited by these results, further study of very fine grinding followed by hydrolysis/fermentation is recommended.